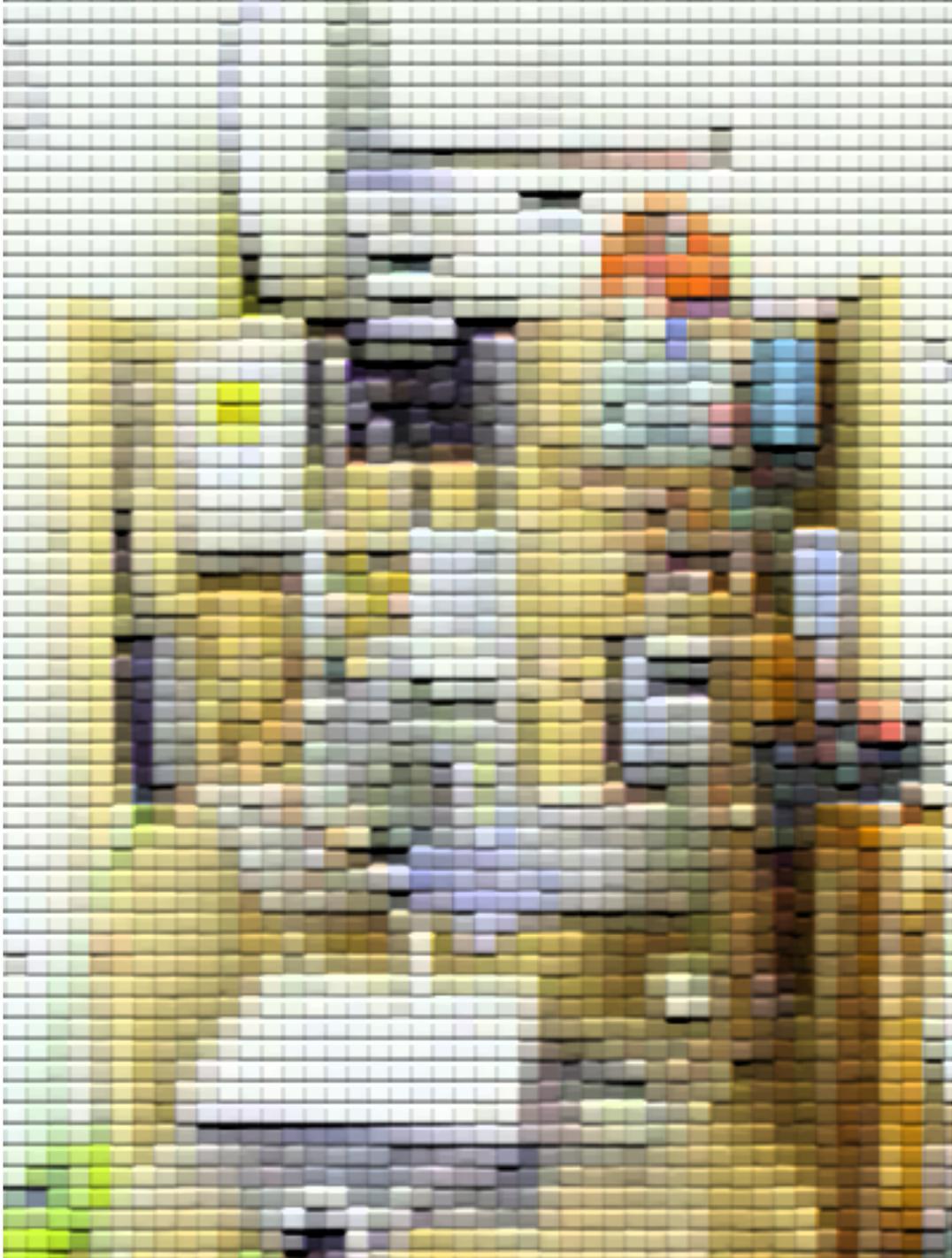


# HydraRaptor

The story so far



by Nophead

# Introduction

This document collects the blog posts from [hydraraptor.blogspot.com](http://hydraraptor.blogspot.com) into one pdf so as to provide easy off-line access and also to preserve an archival copy of the work.

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Gary Hodgson, 2012

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# Hello

Saturday, 31st March 2007 by Nophead

My friend Wes pointed me to [www.reprap.org](http://www.reprap.org) and I immediately decided it was what I going to do with part two of my life. I have been collecting motors and other "useful" junk for years and have at last found something interesting to do with them. My hobby, starting as a child, used to be electronics but it is increasingly hard to find something to make that you can't buy cheaper and better. Consequently I haven't built anything at home recently. My skills lie in electronics and software and I can get by in woodwork and metalwork which I learnt from my father who was a patternmaker by trade. This project involves all these disciplines plus material science and chemistry which I know virtually nothing about but am interested to learn more.

In short, making machines that make other machines is the perfect hobby for me. Hopefully my experiences along the way may be interesting to others so I decided to start this blog.

# Chicken and Egg

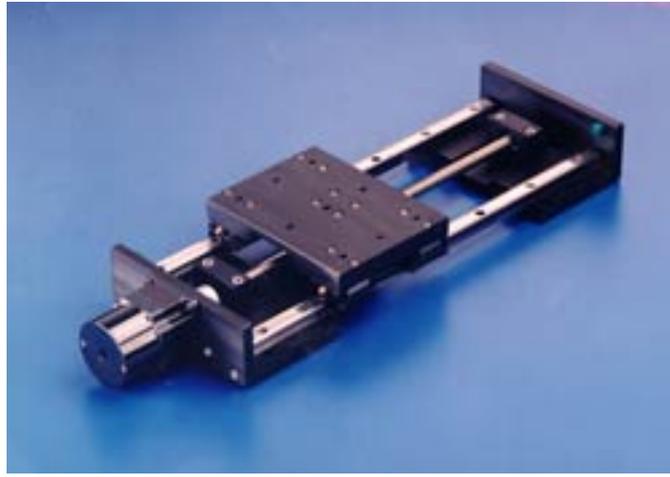
Saturday, 31st March 2007 by Nophead

The problem with making machines that make themselves is how to make the first one! A bootstrap machine has to be made by hand first. This has come to be known as a RepStrap machine in the RepRap community. Lots of people are trying different approaches using whatever materials are easy to come by locally. Wood, Lego, Meccano, copper pipe and drawer slides have all been used by different RepStrappers. The machine needs three axes of motion and an extruder head to extrude molten plastic filament. Most RepStrap machines use threaded rod as a means of creating accurate linear motion from a stepper motor for the axes.

This was the approach I was planning to take when I started looking at this in mid January. I had a look at how professional CNC machines are put together and saw that the prices are a lot more than I wanted to pay but the accuracy and speed was a lot better than I could hope to achieve with drawer slides, etc. I had a quick look around to see if I could get anything second hand or from the surplus market. To my surprise I found an XY table on ebay for \$400 which has a super small step size of 6 um but is able to move quickly and has very high stiffness.



This gave me the idea that I could make a very accurate machine that is also stiff enough to do milling. I found a Z axis on CNCzone for \$150 and the project was born.



# Worth the wait

Sunday, 1st April 2007 by Nophead

The XY stage turned out to be a really nice piece of kit. It is an XYR-8080 from NEAT, details [here](#). It also came complete with a pair of MDM7 stepper motor drivers. These are bipolar, constant current, micro-stepping with anti-resonant circuitry and opto isolated inputs, i.e. top of the range.

Perhaps I should explain each of these terms :-

## Bipolar versus Unipolar drive

Stepper motors usually contain two electromagnets which need to be energised in one of two magnetic polarities, giving four combinations or phases. If this is done with a single coil per electromagnet then the electronics must be able to drive a positive or negative current into each coil. This is bipolar drive and requires four transistors per coil, i.e. eight per motor. Alternatively the coils can be centre tapped which effectively creates two coils per electromagnet wound in opposite directions. One of these can be energised at a time to produce opposite magnetic fields. This only requires one transistor per half coil, i.e. four per motor. The advantage of unipolar is that the electronics are cheaper but as only half of the windings are energised at one time the amount of torque available from a given size of motor is less.

The field produced by an electromagnet and hence the torque of the motor is proportional to the number of turns times the current. The maximum current that can be applied is limited by the maximum allowable temperature rise. The heat generated in the windings is proportional to current squared times resistance. This means that if a unipolar motor is operated in bipolar mode then the maximum current is root two times less because the resistance of the full winding is double that of the half windings. However, the number of turns is doubled so the torque is root two greater.

## Constant current versus constant voltage

The simplest way to drive a stepper is to apply a constant voltage to the coils. The problem with this is that when a voltage is applied to a coil the current builds up gradually at a rate proportional to the voltage divided by the inductance until it reaches the steady state defined by the voltage divided by the resistance. This causes torque to fall off with speed because at higher step rates the current does not get time to reach its full value before the next step.

A better driver system is to apply a much higher voltage to the coil to get the current to rise quickly and then turn it off when it reaches the correct value. The current then starts to fall at which point the voltage is applied again. This on / off switching occurs at a high enough frequency to avoid producing audible noise.

## Micro-stepping

This is a technique to increase the number of steps per revolution by varying the current

in the two windings in a sinusoidal fashion. In this case it increases the number of steps from 200 to 2000 per rev. As the screw threads have half an inch travel per rev this gives me a step size of a 4000th of an inch or just over 6 micrometers. The target for RepRap V1.0 aka Darwin is 0.1mm resolution so I am well within that that! The only downside is that the maximum travel is only 150mm in each direction compared to Darwin's 300mm.

Another advantage of micro-stepping is that it produces smoother running at low speeds.

### Anti-resonance

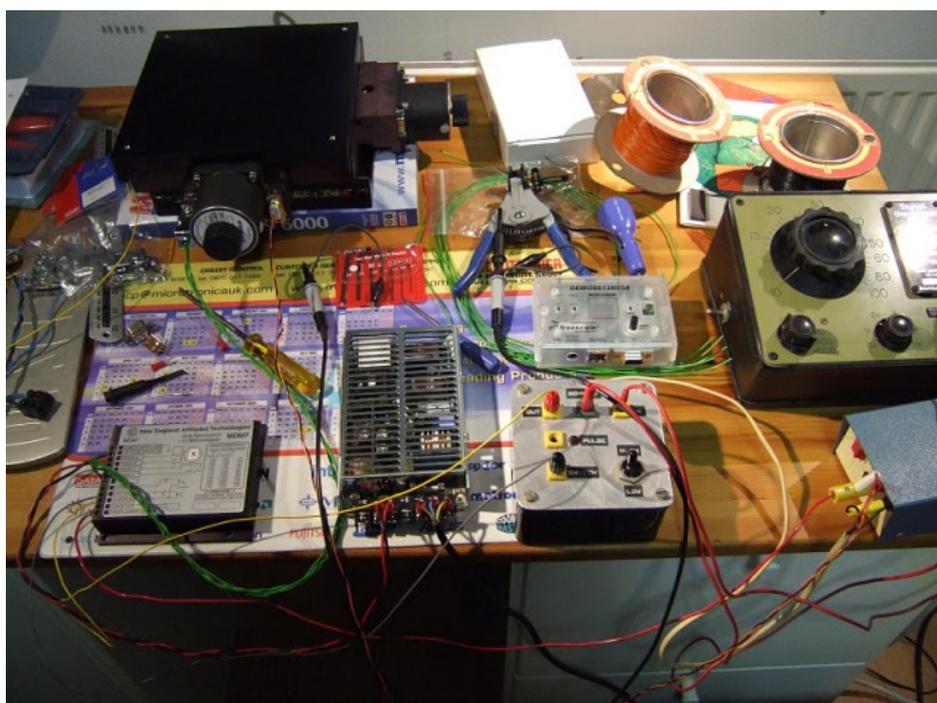
Because the force applied by the motor increases as it is displaced from its resting position it behaves like a spring. This together with the mass of the rotor and the load forms a resonant system. If the step rate gets close to the resonant frequency oscillations build up and the motor gets out of step and / or stalls. This is a major problem with high speed operation of stepper motors. An anti-resonant drive monitors the drive waveforms to detect when resonance starts to occur and adjusts the drive current to dampen it down. This allows the motor to be stepped through its resonant band to achieve higher speeds. Clever stuff!

### Opto isolated inputs

The step and direction inputs are electrically isolated from the drive electronics by opto couplers. This avoids heavy motor currents sharing the same ground path as the logic signals, which can cause signal corruption.

The XY stage also includes hall effect limit switches and 2000 step shaft encoders. A great find, the challenge now is to build a machine that does it justice.

Here it is being put through its paces with a signal generator on one axis.

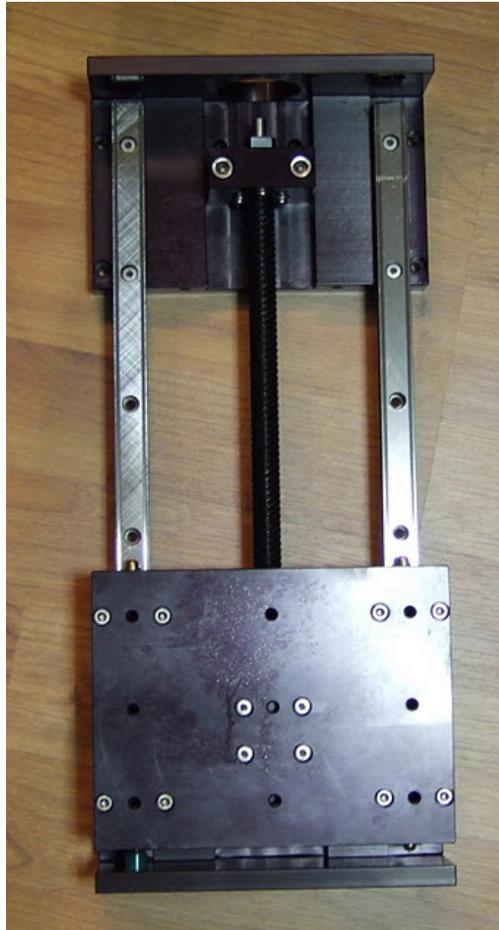


It can easily handle step rates up 6kHz which is about 40mm per second. With a bit of ramp up and ramp down I think it would go well above 10kHz. Also I have the full windings connected for maximum torque. The motors are centre tapped so I have the option of using half the winding. This gives root two less torque but one quarter of the inductance, so should be better for higher speeds if needed.

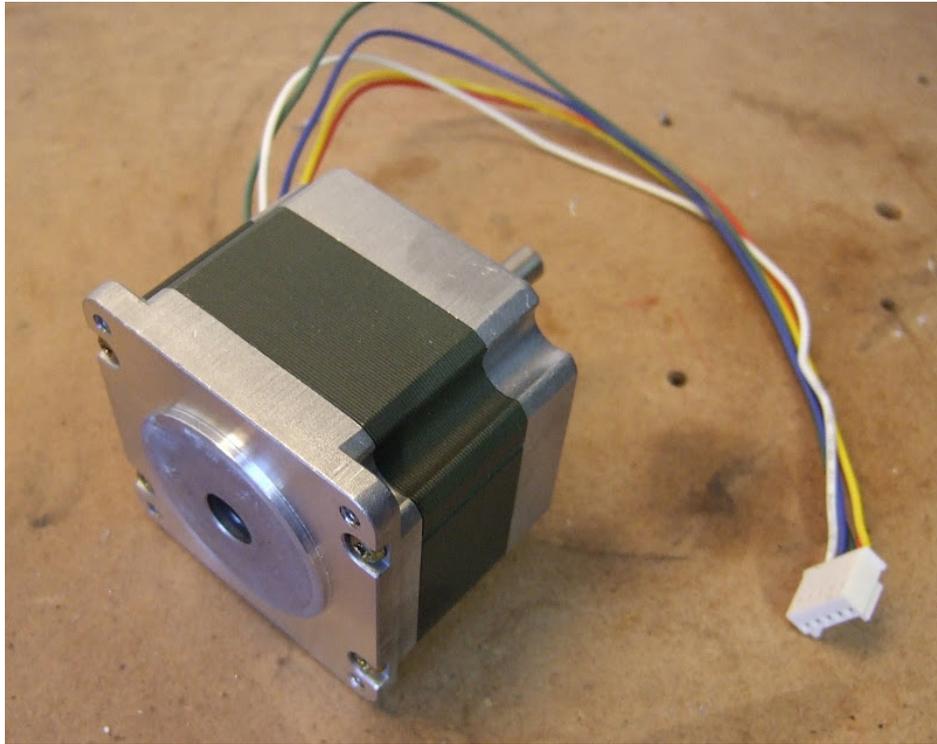
# Straight up

Sunday, 1st April 2007 by Nophead

I forgot to describe the z-axis. Not quite such a bargain as the XY table as it does not include a stepper motor, limit switches or electronics but I am pleased with it all the same. It is very solid so I should be able to mount any type of head I want on it.



It has a mount for a Nema frame motor. I have a few of these lying around but unfortunately the shaft exits from the wrong end so I will have to mount one on pillars.

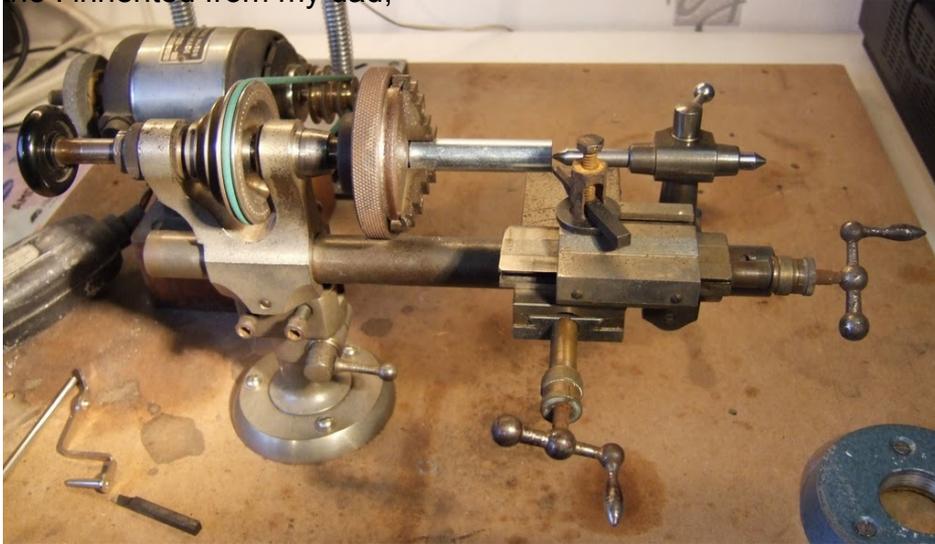


These are 1.8 degree step motors so with half stepping I will get 400 steps per rev. Each rev of the leadscrew moves the carriage 20 mm so I will get a resolution of 0.05 mm. It doesn't need to move very fast so I will try to get away with a simple constant voltage unipolar drive circuit.

# Its a plan

Sunday, 1st April 2007 by Nophead

Having obtained some accurate and strong axes at a reasonable price a plan was starting to form. I decided to make a small but highly accurate milling machine. With this, and the small watchmaker's lathe I inherited from my dad,



I should be able to make a plastic filament extruder. I intend to mount this on the z-axis to make an FDM machine capable of making the plastic parts of the RepRapDarwin. I should also be able to mill and drill the Darwin PCBs. Once I make the Darwin I will be synchronised with the RepRap project and thus able to make the successive generations, whatever they may be, because the RepRap idea is that each new generation can be made by the previous one.

That was my original aim but my axes should out perform the Darwin axes in all respects except build volume. Darwin aims to achieve 0.1 mm accuracy with a 300 mm cube build area. I expect to get 0.006 mm accuracy on X and Y and 0.05 mm accuracy on Z over a 150 mm cube. That means rather than just using my machine as a RepStrap I will continue to use it for anything that doesn't need the larger build area. I then got the idea that I would be using many different heads on the same Cartesian engine, hence the name HydraRaptor. Initially these will be manually exchanged but I have a plan to mount the heads, spoke like, on a rotating wheel fastened to the z-axis.

# Starting off on the wrong foot

Monday, 2nd April 2007 by Nophead

My machine should probably be made from metal to give it enough stiffness for milling. However, I decided to prototype it in MDF first because it is much quicker and cheaper to work in wood. As it turned out it was just as well I did!

MDF is my favourite wood because it comes perfectly flat, with straight edges and right angle corners. No grain or knots to worry about either, the only problem is the dust which gets everywhere and is allegedly carcinogenic.

I have a foldaway workbench in the garage made from an old front door with a sheet of MDF over it. The door's original hinges are used to let it swing up from the wall and it has hinged legs that drop down as I pull it out. This allows us to keep a car in the garage, something very few households seem to do these days.



The bench has woodwork and metalwork vices and three interchangeable stations where I can mount my bench sander, drill press and band saw. These are stored on a shelf above the height of the car.



Unfortunately when I first put the shelf up I used the wrong sort of plugs for hollow breeze blocks. One day my wife and I heard a crash which sounded like a car crash in the front garden. We ran to the window but nothing was happening outside. We had just got a new TV with surround sound so we thought it must have been part of the film we were watching. The next morning when my wife went into the garage she found the shelf and all my tools on top of her car! It did so much damage she still hasn't forgiven me ten years on.

The first thing I did to start my build was to cut a base board 500 mm square from a sheet of 18 mm MDF. I placed this on the bench while I adjusted the band saw for the next cut. Somehow I managed to knock the sheet off and it landed on my big toe. The pain was the worst I have ever experienced. It left a pair of 18 mm tram lines across my leather shoe as you can just make out below :-



This is what it did to my toe :-

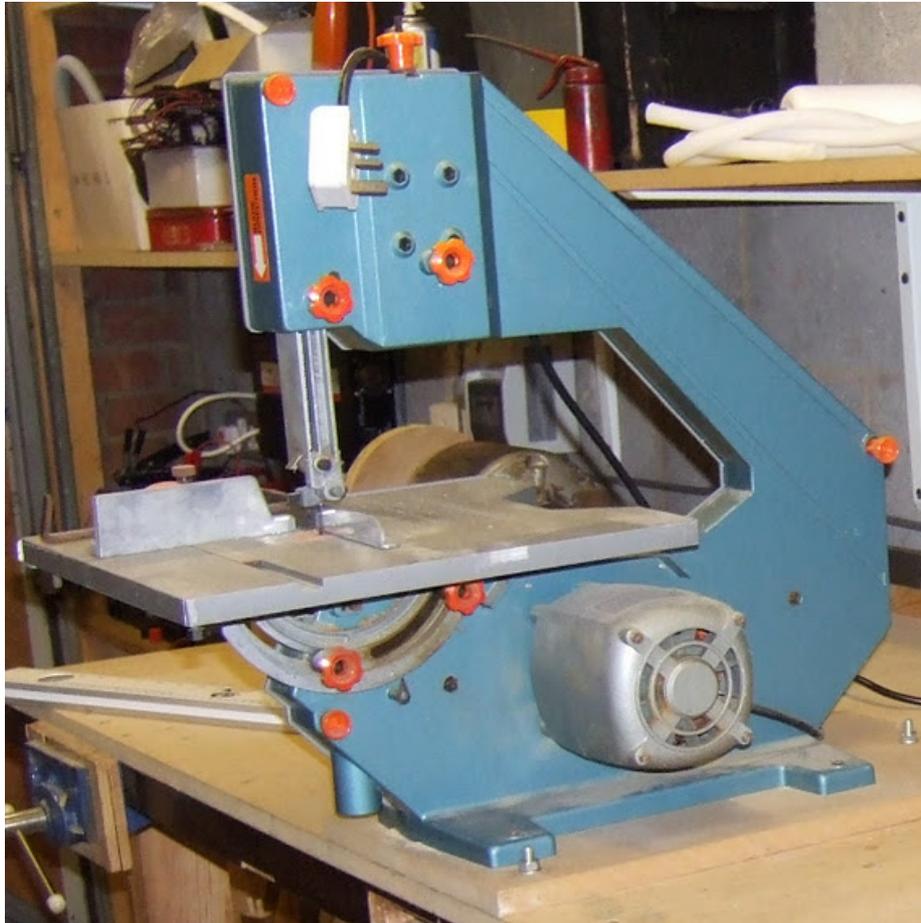


That put an end to that evening's work and left me limping for a couple of days. The toe recovered but the shoe didn't. I can see now why my dad always wore steel toe capped "totector" boots when he was working.

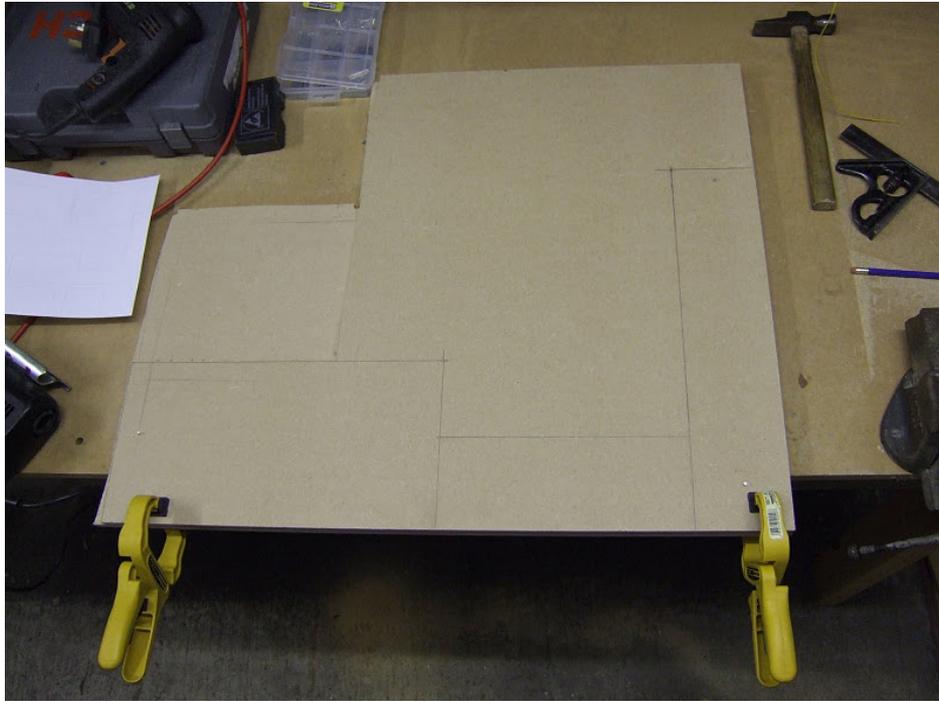
# Up a blind alley

Tuesday, 3rd April 2007 by Nophead

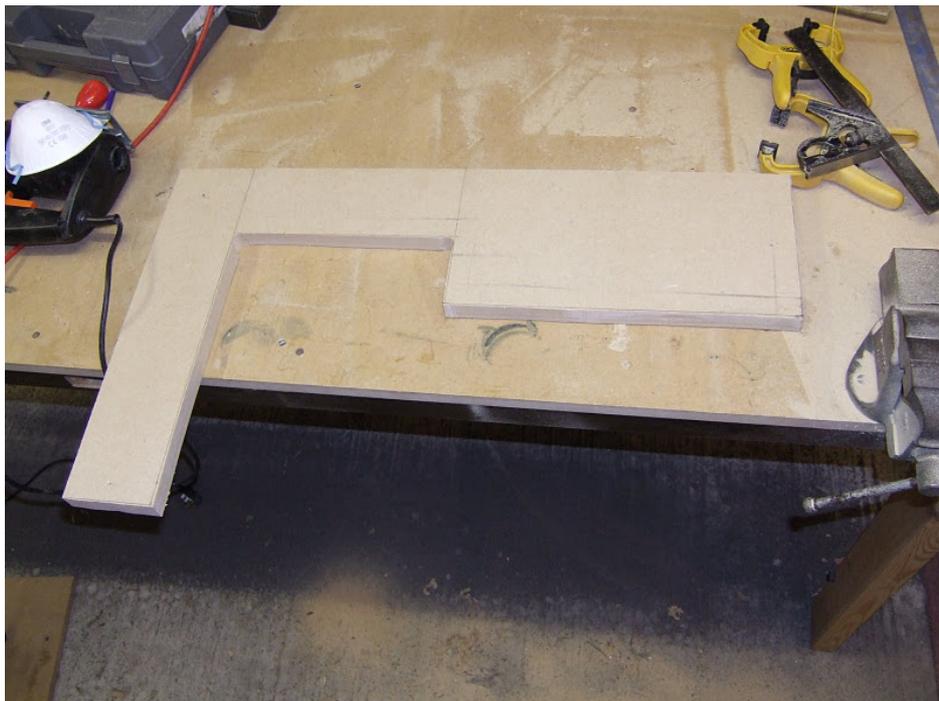
The basic requirement of the mechanical design is to suspend the z-axis solidly 150 mm above the centre of the XY table with enough overhang to allow the table to move  $\pm 75$  mm in each direction. Inspired by the shape of my bandsaw I decided to make a G shaped construction.



In order to get both sides precisely the same, I cut a sheet of 12 mm MDF diagonally and then nailed the two halves together. This allowed the original accurate edges to form the corner between the back and the base on both pieces.



I then drilled large holes in the inner corners and cut the shape out with the bandsaw and a jigsaw. I tidied up the cut edges with a bench sander.



I made the joints with 12 mm beading, PVA glue, screws and nails.



Here is the finished article.



And here it is with the axes fitted and a large set square for scale. I used this to check the orthogonality and it was spot on.



Unfortunately as soon as I had finished it I realised I had made a really basic mistake. All the right angles were braced by at least one sheet of MDF in its strong direction so I thought it would be pretty solid. However if I pushed hard against the side of the z-axis I could move it about 1 mm. Although this would be stiff enough for extruding plastic it would be no good for milling. What I had failed to take into account was that there is nothing to brace it against twisting around the vertical axis. Adding sides and a top to complete the outer box would have helped. Another idea I had was to fill it with concrete. When I thought about it a bit longer I realised this is why CNC mills are usually based on a gantry design. Reluctantly, I decided to scrap an entire weekend's work and start again without ever powering it up.

# Back on track

Wednesday, 4th April 2007 by Nophead

They say you only learn by making mistakes. Well I learned that for a structure to be stiff it has to be braced against twisting as well as bending. Wasting a whole weekend certainly hammers the point home!

My second attempt was smaller, much sturdier and a lot easier to make. I completed it in two evenings as opposed to two days and with no injuries! I made all the pieces out of 18 mm MDF sheet whereas the first attempt was a mixture of 18 mm, 12 mm and 8mm. All the pieces were rectangles so I got them cut at B&Q where I bought the wood. I used two 1200 mm by 600 mm sheets and all the cuts were free. Here is the kit of parts I came home with.



I used 12 mm beading and PVA glue again to make the joints, but this time I used more screws and no nails.



Here is the finished woodwork. No detectable movement no matter how hard I push on it.



And here it is with the axes installed. The x-axis is wired to its controller and a power supply. This is a small 24V 100W switcher made by Sanken Power Systems. I chose this from the random selection of PSUs I have collected because my z-axis stepper is 24V and the XY controller can run from anything between 24 and 60V. I don't know if I will need a 12V rail yet, I am hoping to get away without it.



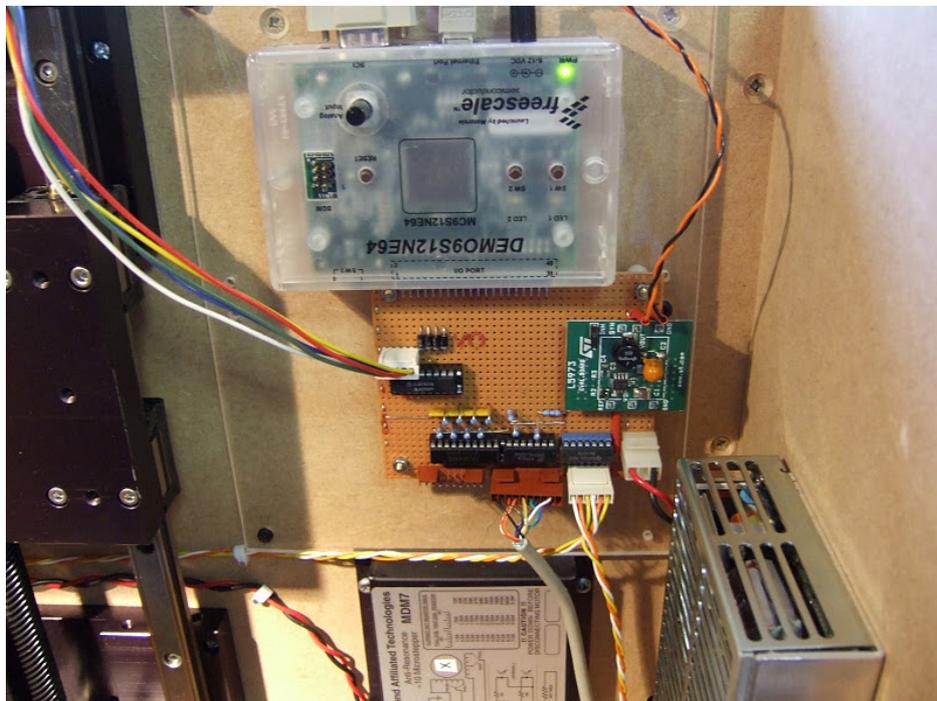
Wiring and electronics next.

# Brain Box

Thursday, 5th April 2007 by Nophead

The RepRap machine uses a network of Microchip PICs plus a comms board to control the axes and the extruder(s). The controller boards are multi-purpose so this gives a flexible scheme for experimenting and extending the machine. This topology does not make so much sense for HydraRaptor because I have invested in a set of professional quality axes which I hope to be using in a stable configuration for a long time. Using three controller boards plus a comms board to drive these is a bit over the top.

Instead I have chosen to use a demo board that I had lying around to control all three axes. This is a DEMO9S12NE64 from Freescale Semiconductor. It has an on-chip Ethernet controller and a good array of analog and digital I/O ports plus serial ports, timers, etc. It comes with a free TCP/IP stack and a CodeWarrior IDE, C compiler and debugger.



I bought this a couple of years ago from Digikey to acquaint myself with Ethernet and TCP/IP but had not really done anything with it. Strangely, although the chip has masses of I/O, only a subset of this is available at the connector and some of these lines are also connected to the on-board switches and LEDs. Annoyingly the C compiler has a 12K code limit but that should not be a problem for this project. The IDE and debugger are not the best I have used and I have seen the compiler produce some terrible code. There is no excuse for this as the instruction set of the 9S12 is fully featured and well suited to C, unlike say the PICs. Sadly most C compilers I see these days produce worse code than one I used 20 years ago.

It comes with a preloaded monitor program which allows code to be loaded into on-chip flash via a serial port and then debugged at the source or register level with breakpoints and single stepping,

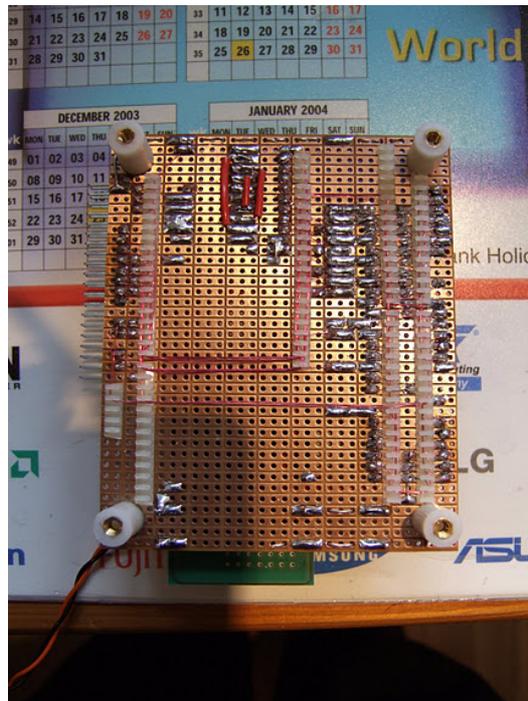
etc. All in all the dev kit is not too bad, certainly nicer than the Microchip stuff.

I will use Ethernet to link my machine to the PC as that gives me complete freedom where I locate it. There is enough I/O to drive an extruder as well as the axes. I may well do that initially, but eventually I will use one of its serial ports to drive a network of head controllers.

One snag of using the demo board is that it is 3.3V volt logic. My XY table uses 5V logic so I had to do some level translation and that is most of what the veroboard underneath is about. The outgoing signals to the opto inputs of the stepper controllers are driven by a 7407 open collector buffer. The proper way to handle the incoming signals would be to use a level translating buffer chip but I didn't have any to hand and I suspect they are not available in leaded packages as most 3.3V stuff is surface mount. Instead I buffered them with a 74LS244 and then used potential dividers to drop the voltage. If I had not buffered first I would have reduced the noise immunity in the long leads around the machine which would not be good. This way it is only the noise immunity across the board that is slightly compromised.

Other things on the board are the z-axis driver and a 2A switching regulator which steps down the 24V to 5V to drive the level changing logic. This is actually an L5973 evaluation board from ST. Doing this with a linear reg would waste a lot of power and need a big heat sink. The DEMO9S12NE64 comes with its own 6V mains PSU but I found it works fine fed from 5V as well.

I wired the board using the Verowire system, see [en.wikipedia.org/wiki/Wiring\\_pencil](http://en.wikipedia.org/wiki/Wiring_pencil).



This is quite a quick way to produce high density prototype boards but it is a bit fiddly and requires a lot of concentration. It is not easy to make changes afterwards either.

In summary I was able to cobble together the control system from bits I already had.

# Bundle of nerves

Friday, 6th April 2007 by Nophead

The wiring is fairly straightforward. The power rails are 24/0.2 and the sensors are connected with multi-core 7/0.1 screened cable salvaged from a mouse's tail. The rest of the connections are 7/0.2. The manual for the MDM7 stepper motor controllers recommends using screened cable for the motor connections because they are switching at hundreds of kHz. I couldn't find any that would handle the current so I used twisted pairs which are the next best thing. I made these by twisting two pieces of 7/0.2 wire with a drill and then put them inside plastic tubing to protect them.

I recycled a mains inlet and switch from a broken PC power supply.



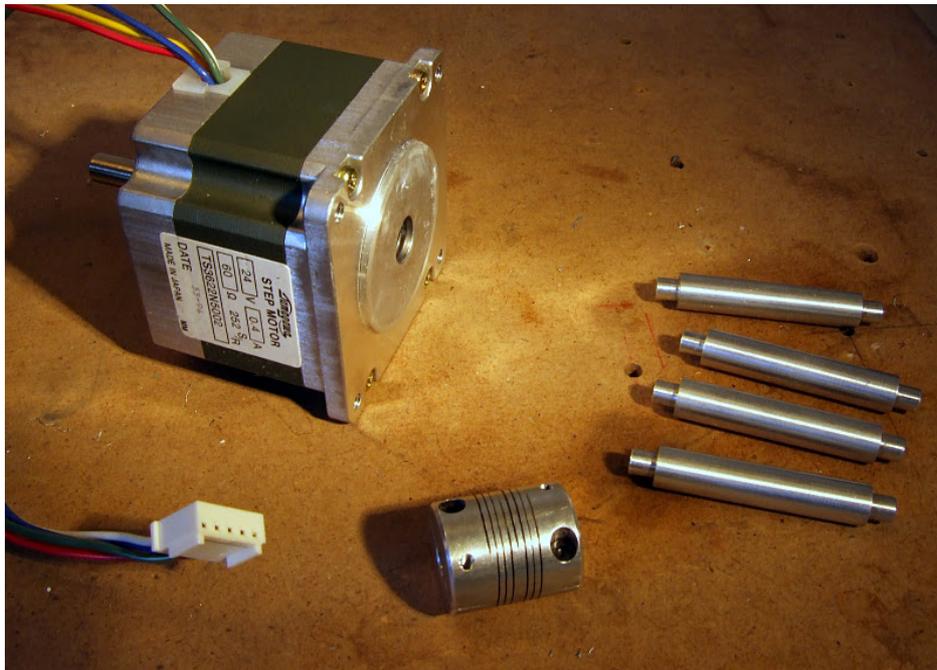
I also got a 0.2 inch 2 pin connector from it for the 24V feed to my I/O board. The rest of the I/O connections are 0.1 inch headers.

Again, I had all these parts lying about for years so my wife is pleased that I am starting to use up some of the "junk". The only things I have had to buy so far are the axes, wood and three 9 way D type connectors.

## ... like a bride's nightie!

Saturday, 7th April 2007 by Nophead

The z-axis was advertised as accepting a NEMA23 dimension motor without any adapter flanges. The motors that I have are more than 10 years old and I don't have any data on them so I don't know if they are true NEMA23 or not but they weren't quite compatible in two ways. The shaft exits from the wrong end and the holes are tapped M4 but the holes in the frame are also tapped M4 and blind. I resolved this by mounting it upside down on some aluminium pillars that were nearly the right length. I had to turn them down in the lathe, drill them and tap them to insert M4 bolts with the heads cut off. The result was very solid because the pillars exactly fit the semi-cylindrical recesses of the motor.



I used a flexible coupler, shown above, to join the motor shaft to the drive screw. This allows for slight misalignment. A cheap alternative can be made from plastic or rubber tubing and pipe clips but I had a couple in my junk collection so I used one. This may have been a mistake because the z-axis is very noisy when it is running. This is made worse by the fact that it is mounted on an MDF box structure which resonates. A softer coupling may help here. Another idea I had was to fill the box with something to dampen the sound, fine sand perhaps, I am open to suggestions.

BTW, if anybody is interested, there were more of these axes available [here](#) when I last looked.

The z-axis only needs to move relatively slowly so I used a simple unipolar drive circuit based on a [ULN2803](#) octal darlington driver chip. I paired up the channels to get enough current because with only 3.3V inputs they are derated somewhat. The 2803 has internal clamping diodes to protect it from the back e.m.f. generated when a winding is turned off. Rather than tie these to a zener off the positive rail, like the RepRap [version](#) does, I clamped the outputs to ground with some external diodes. This makes use of the fact that each centre-tapped winding behaves like an auto

transformer, so if you stop one end going below zero you stop the other end going above twice the supply rail, in my case 48V. This technique has the advantage of returning the energy in the coil to the supply rail, rather than dissipating it in the zener. It has the slight disadvantage that if you disconnect the motor while the power is on you risk damaging the driver. I used fast recovery rectifiers salvaged from the same broken PC power supply I mentioned before. These will perform better than ordinary rectifiers if I do any high frequency PWM for micro stepping.

The motor got quite hot when it has been on a while, leveling off at about 60°C. It is, after all, dissipating about 19W. While I didn't think this was a big problem I decided to stick a spare CPU heatsink and fan on the top. I ran this from 5V rather than 12V to keep the noise down. It reduces the temperature to about 40°C. With a constant voltage drive, keeping the temperature down stops the torque falling off due to increased winding resistance.



The next step is to write some code and test the axes.

# Know your limits

Sunday, 8th April 2007 by Nophead

The XY table boasts Hall effect limit switches with a repeatability of  $\pm 2.5 \mu\text{m}$  so I should have no problem getting a repeatable homing position to the nearest  $6 \mu\text{m}$  step. They do however have quite a lot of hysteresis and activate some distance from the actual physical end stop. In my first cut of the code the homing routine steps quickly until it sees the negative limit and then steps slowly forward until it sees the limit go away. It sets the position at this point and then ignores the limit from then on so it can achieve the full range of travel. I am not sure whether both positive and negative edges of the limit signal have the same accuracy. I will get more idea when I write the shaft encoder software. These have an index pulse so, no matter how inaccurate the limit switch is, I will be able to get an absolute fix on the position to within one shaft encoder step, which is the same as one stepper microstep.

I haven't used the positive limits yet and I can't think of a reason for needing them except for possibly an automated self-test. I will use the shaft encoders to check that the table is where I think it should be and halt if I find a significant discrepancy. That would indicate a firmware bug, tool crash or hardware failure.

The z-axis did not come with limit switches so I had to improvise. I wanted repeatability to within one half step, i.e.  $50 \mu\text{m}$ . The software knows what the shaft position modulo 8 is because it knows the phase pattern applied to the motor. That means it only needs a limit switch with repeatability better than  $0.4 \text{ mm}$ . I decided to try a micro switch to see if I could find one good enough. As you can see I have managed to amass quite an extensive collection!



I picked one of the small ones on the bottom right and it seems to do the trick. Again it has significant hysteresis as one would expect. My homing routine steps upwards at speed until it activates the switch and then steps down slowly until the switch opens again. At this point I AND the motor position with 7.

Once the homing was sorted out I was ready to test the accuracy.

# Pen pusher

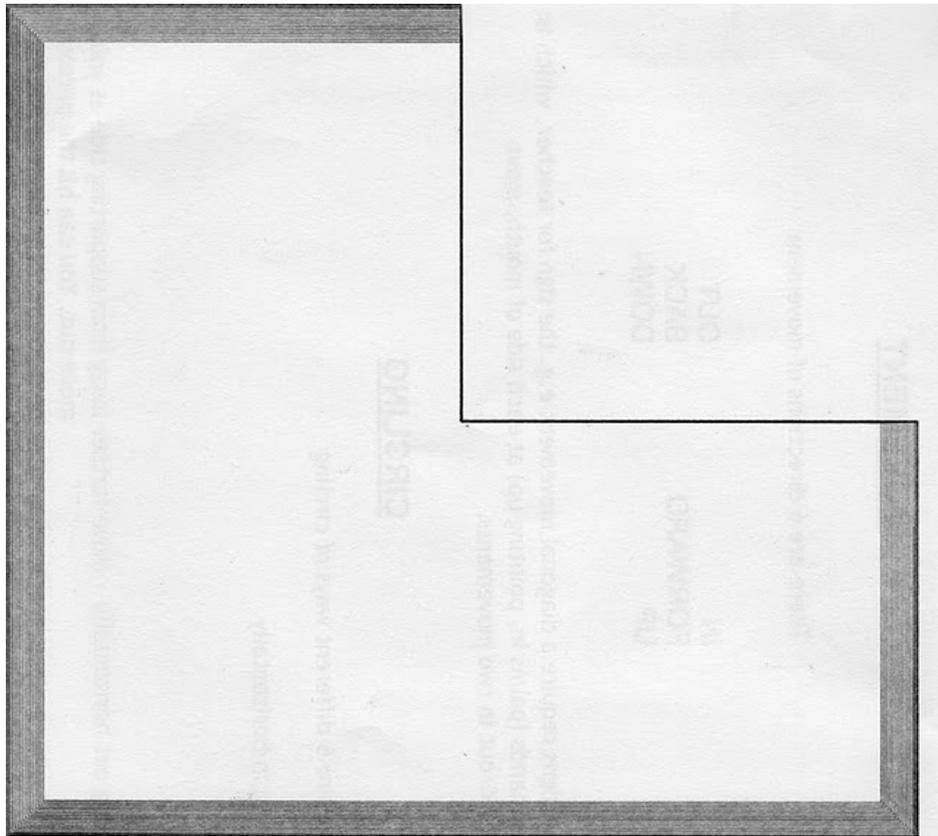
Monday, 9th April 2007 by Nophead

As others have done before me, I decided to test the Cartesian system by turning it into an over engineered pen plotter. I used the refill out of a Fisher Space Pen which apparently "is the most advanced writing instrument in the world". If so, when controlled to a precision of 6  $\mu\text{m}$ , it must make HydraRaptor the most advanced writing machine in the world! I can't think what I would use it for apart from forging signatures.

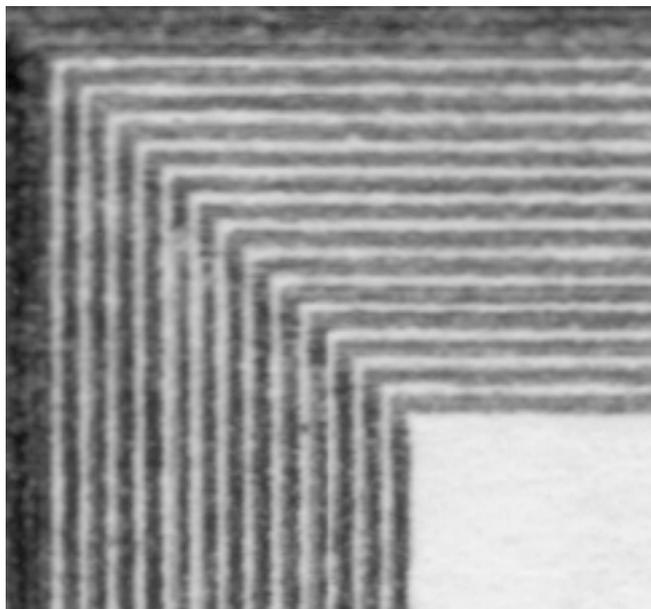
I suspended the pen from the z-axis on a random bit of aluminium using a lump of PolyMorph. This made a perfect mount because I pushed the pen through while it was still molten. There was no play, but if the z-axis were to overshoot, it would just pop the pen out rather than ram it into the table.



I ran a simple program which went from the origin to one edge, around three sides and back to the origin again. It then repeated this, stepping in by 0.2 mm each time. I soon realised the line width was bigger than 0.2mm so I stopped it and ran it again with a step size of 0.4 mm. This left a gap between the lines and produced the pattern below.



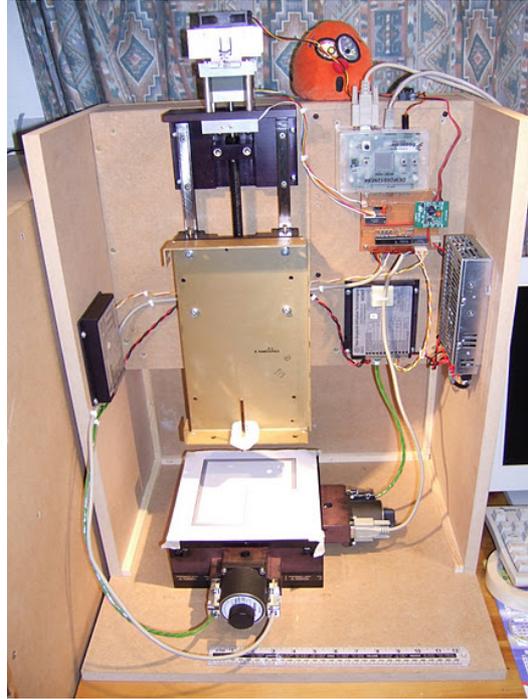
Here is the top left corner magnified.



You can see the corners are pretty good considering the table was travelling about 4 cm per second with no acceleration, deceleration or pause as it turned. At this resolution the graininess of the paper is the most significant distortion.

The paper was stuck to the metal top of the XY table with masking tape. I set the height of the pen by stepping it down until it just started to leave a mark on the paper and then one step more. The paper was about 0.1 mm thick so that meant the pen was pressed about half way into it. As you

can see from the first picture the pen never left the paper so the table must be pretty flat and its movement true. Here is the machine in action :-



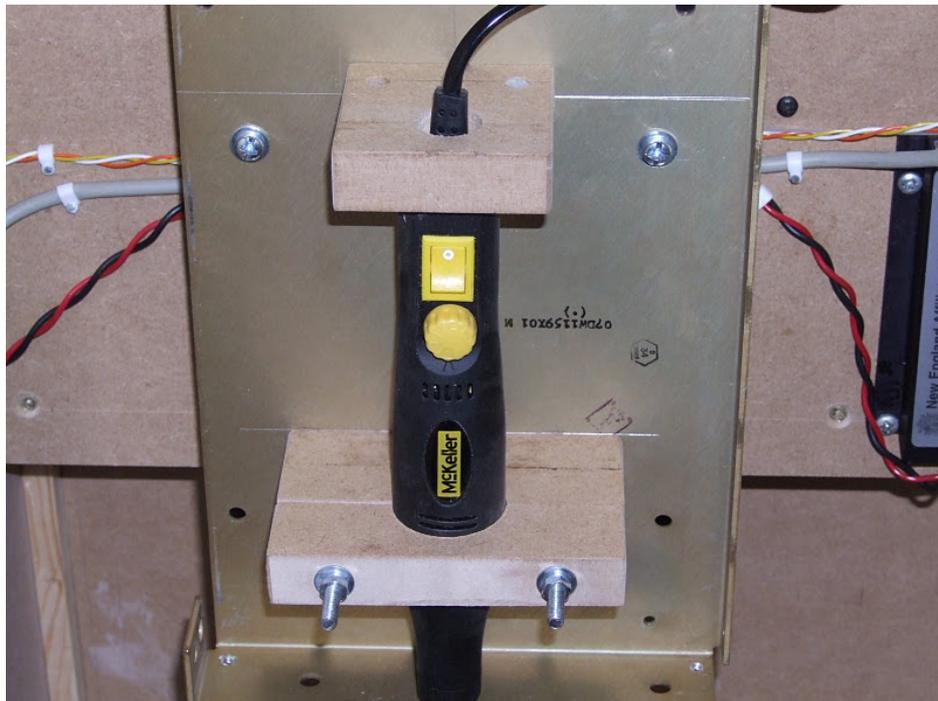
The results look promising, time to have a go at milling next.

# Trouble at' mill

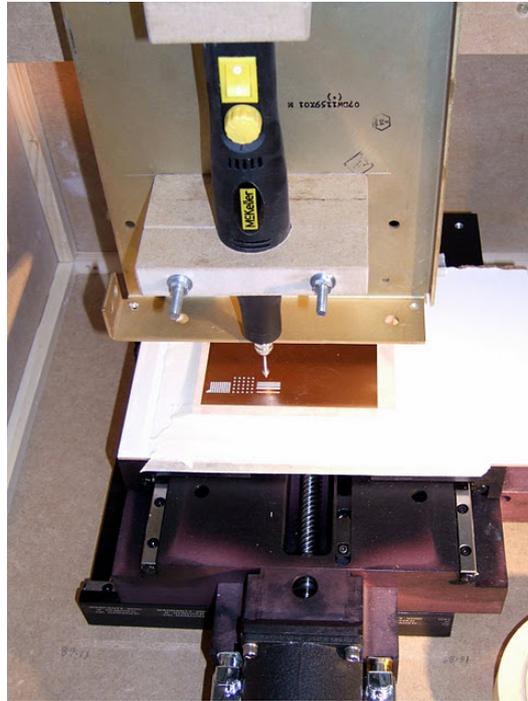
Tuesday, 10th April 2007 by Nophead

Having established that the axes were all working well I decided to do some tests to check the feasibility of milling PCBs. I originally planned to use a Dremel but its shape looked difficult to mount. I saw a cheap alternative that was cylindrical so I decided to give it a try.

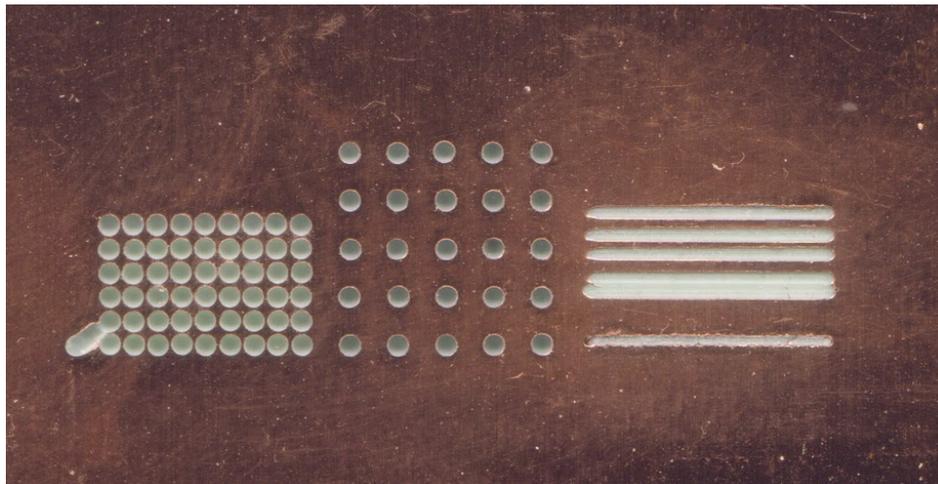
I made some mounts out of MDF and these were bolted onto a 2 mm aluminium plate which had some folds in it for strengthening. I could not find a source of countersunk bolts long enough to go through the top mount. Instead I used some shorter ones and made captive nuts out of PolyMorph. I did this by first drilling clearance holes from the back of the mount to a depth just longer than the bolts. I then drilled 5 mm holes through the thickness of the MDF to meet them. I filled these with molten PolyMorph. When it had set I drilled it for tapping but I found I could just screw the bolts in and they cut their own thread. This technique seems to make a successful fastener system.



I asked a friend who works for a company that owns a professional PCB mill what they place under the PCB while it is being drilled. He was kind enough to send me a sample. It is 2 mm hardboard laminated with a thin layer of hard, melamine like, substance on each side. I have not found a source for this yet but my wife, ever keen to see "junk" turned into something useful, suggested I used some laminate flooring offcuts we have in the garage. I will give this a try, but for my initial test I used the hardboard sample. I just taped it to the top of my XY table with masking tape and taped a piece of PCB material on top. The arrangement is shown below :-



And here is a magnified view of the results :-



The diagonal on the far left is where I broke a drill due to a typo in the code: `step_x` instead of `step_z`. The drill made a valiant attempt at being a milling bit before it snapped. Not a good start, this could get expensive!

The holes on the left are 1 mm on a 50 thou grid. So far I have tried to keep all the units in this blog metric but PCB measurements are traditionally done in 1000 ths of an inch because most component leads are on a 0.1" grid. Again this was a bug but it turned out to be a good test to show drill run out. The gaps between the holes should be 0.27 mm or about 10 thou.

The holes in the middle are on a 0.1" grid which was my original intention. The holes don't actually go all the way through due to end play in the drill.

The bottom slot on the right was done with the conical tool shown in the picture below :-



This has quite a fine tip but an abrasive surface rather than cutting flutes. I estimate the channel is about 20 thou but the edges are a bit ragged, particularly the top edge. The tool rotation was clockwise and the travel left to right. This means the bottom edge was climb or down milled and the top edge conventional or up milled. Climb milling is recommended for a better finish so I need to organise my tool paths to go clockwise around the outside of tracks.

The three tracks were produced with a rose burr tool like the one on the far right but smaller. The remains of it are shown in the middle. I snapped it after the test with another accident. This tool created a smoother cut. Again, the bottom edge is cleaner. The bottom track is about 20 thou, the middle one 10 thou and the top one 15 thou. The gap between tracks is about 30 thou.

My target for through hole PCBs is 10 thou tracks and 15 thou gaps. This allows one to get a track between two 60 thou pads 0.1" apart, i.e. between the legs of a chip.

Things I learned from this experiment :-

- Not surprisingly, the cheap (£20) drill was not up to the job. It has about 1 mm end play and noticeable lateral play. It is also very noisy when mounted on the machine. I have ordered a 30000 RPM 600W laminate trimmer for £26.49. Again, I will not know the quality of the bearings until it arrives, could be another mistake.



If that does not work I might try a Dremel or perhaps one of these :-



This is an 800W router spindle motor for about £80.

There is a good article on how to make your own PCB router spindle [here](#) but I think my lathe is too small.

- The 2mm aluminium plate is not stiff enough, I got a 6mm slab from eBay to replace it.



- The milling bit, before I broke it, was too big. I got an eight piece "carbide circuit board maker" kit from [Drill Bit City](#) for \$23. They were very helpful and efficient. Again the good stuff is on the wrong side of the pond so the shipping was another \$12.



- They also sell carbide end mills down to 5 thou. These are quite pricey and delicate but I might try some when the software is stable. I will need smaller clearances for fine pitch surface mount.
- I need dust extraction and it needs to be a fairly strong suction to lift the copper chips. I can buy a 1300W vacuum cleaner from ASDA for about £17.

Despite the deficiencies noted above I think the test was reasonably successful. In fact the current set up could probably produce a working PCB. I will get the software written and debugged before I fit the new parts. A 600W router could do a lot of damage! It would bring a whole new meaning to the phrase "software crash".

# The powers that be

Wednesday, 11th April 2007 by Nophead

When trying to make parts of my machine stiffer I got to wondering about the relationship between a material's thickness and its resistance to bending. It is obviously not a linear relationship because as a sheet gets thicker not only is there more material to resist bending, but the outer layers have more leverage than the inner, so it must be at least a square law. I tried googling this for some time but failed to find a formula. I did find a comment on [CNCzone](#) by somebody that thought he recollected it being a fourth power law. I can believe this because we recently had two versions of a metal box made at work, one in 0.5 mm steel and the other 0.8 mm. While the thin one was quite flimsy the 60% thicker one was very solid. Any mechanical engineers out there?

I came across another fourth power law recently on the website of the company that made my XY table. If you have a servo system moving something from A to B as fast as it can go, then going twice as fast requires 16 times the power. Some video lectures, and a lot of other useful info about servo systems, are here [www.neat.com/products/corner/default.asp](http://www.neat.com/products/corner/default.asp).

The highest power law I have ever come across is that incandescent bulb lifetime is inversely proportional to the 12th power of voltage, see

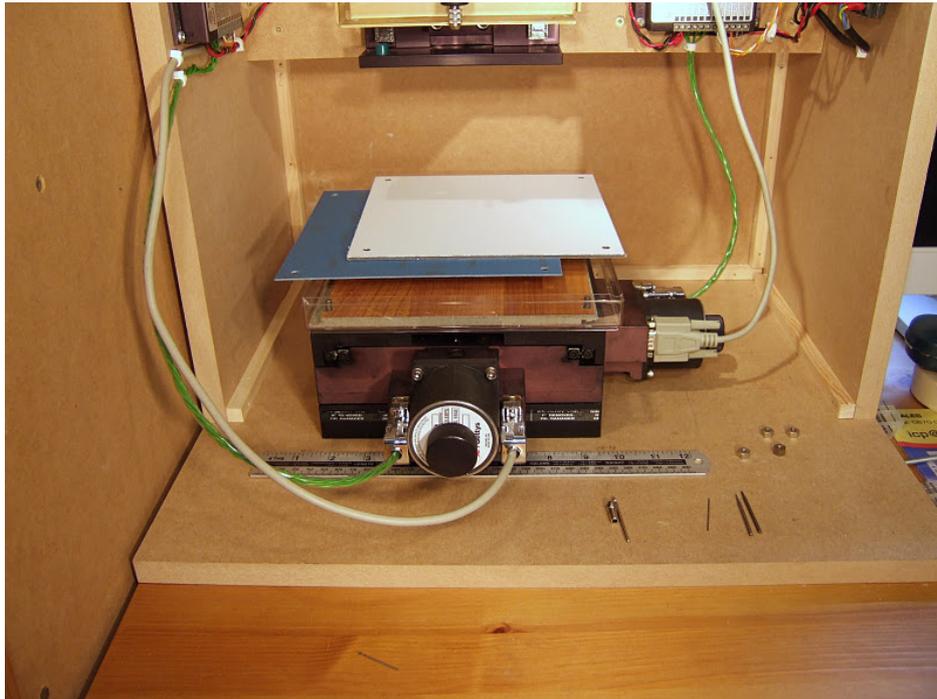
[www.allegromicro.com/en/Products/Design/an/an295012.pdf](http://www.allegromicro.com/en/Products/Design/an/an295012.pdf). Can anybody beat that?

# Stacking up

Saturday, 14th April 2007 by Nophead

You may notice my blog entries slow down a bit as I have now finished catching up so it has become real time. Hopefully I should get less complaints about mixing tenses in a paragraph!

I have made a clamping system to fasten PCB material to my XY table. The test using masking tape worked surprisingly well but I need to be able to turn the board over whilst maintaining alignment for double sided PCBs.



The bottom layer you can see in the picture is a plastic tray to catch the dust from milling. It is the bottom half of a Ferrero Roche chocolate box. They make great boxes but unfortunately my wife does not rate the chocolates much.

The next layer is a sacrificial piece of laminate flooring to support the PCB and prevent breakout when it is being drilled. It seems a shame to cut it up and use it this way but at £6 per square meter this piece only cost £0.17 and I can use both sides at least once.

The blue sheet is single sided PCB material. I will use the machine to route a square aperture in the middle of this at the limits of the XY table's travel. The PCB being made will rest against one corner of the aperture to locate it. Being double sided it will stand proud by 0.3mm due to the extra layer of copper.

The top layer is a 3 mm aluminium and plastic laminate that I will use to clamp the board down on two edges. I will use the machine to route a slightly smaller aperture in it than the layer below so that it overlaps slightly. The other two edges of the board will be held down with masking tape.

The whole lot is clamped by four 2 BA nuts on threaded rods that fit holes in the XY table. My XY table is imperial and the rest of the machine metric!

I am currently working on the firmware. I have replaced the test code I cobbled together just to try things out with an interrupt driven 3D Bresenham line drawing routine. Although I probably will never need to step Z at the same time as X and Y it was easier to code the general case. It makes some interesting sounds when in runs because the motors play a three note chord depending on the gradient of the line.

The code is written in C in an object oriented style even though C is not an OO language. I always tend to code like that and have done so since before I knew what OO was. The three axes are represented by structs that store the position, etc, along with function pointers for stepping and reading limits which is axis dependent. That way I can reuse the same Bresenham and homing code for all three axis.

```
typedef struct axis {
    sword  pos;                // Current position
    sword  min;                // Limits
    sword  max;
    sword  steps;              // Number of steps to do this line
    sword  dir;                // Direction of each step +/-1
    sword  acc;                // Brezenham accumulator
    void   (*set_dir)(bool);   // Virtual function to set direction output (X,Y only)
    void   (*start_step)(void); // Leading edge of step pulse
    void   (*end_step)(void);  // Trailing edge of step pulse
    bool   (*mlimit)(void);    // Read the negative limit
} axis_ty;
```

The next task is to link HydraRaptor to my PC using Ethernet. The demo box comes with a free TCP/IP stack but it is not very efficiently written so I will replace it with my own minimalist version. I will just implement ARP, IP, UDP and ICMP ping. I have done this before so it should not take me too long.

# Slow going

Saturday, 21st April 2007 by Nophead

Not much to report as I have had little time to spend on HydraRaptor this week, should get more done this weekend though.

On the firmware front I got as far as writing the Ethernet PHY driver. This is the part of the Ethernet controller concerned with actually sending the signals down the wire. Back in the days of 10MB Ethernet this was a relatively simple line driver. With 100MB it is a lot more complicated and generally involves a DSP to compensate for signal distortion in the cable. Quite often these are separate chips but the MC9S12NE64 has one built in.

Despite the internal complexity, the interface to a PHY is straightforward. The driver just has to configure it and then wait for it to report that the link is up. One slight wrinkle I came across is that there is a bug in the silicon that drives the activity LED. Apparently the pulse it generates is too short to be seen. You can either stretch it in hardware or disable the hardware control of the LEDs and do it yourself in software, using the pins as general purpose I/O.

The next thing to do is write the MAC driver. This part of the chip is responsible for sending and receiving Ethernet packets.

# **A lot quicker**

Sunday, 22nd April 2007 by Nophead

Here is somebody that works a lot quicker than me: [reprap-wasnt-built-in-day.html](#) !

# Too thick

Sunday, 22nd April 2007 by Nophead

I decided to order the parts to make the extruder so that they could arrive while I was writing the firmware. The official RepRap design I am working to is [here](#). Forrest Higgs has a simpler design [here](#) but as I have a lathe and I don't have a blowtorch I decided to stick with Adrian Bower's original for my first attempt.

I got a lot of the mechanical parts from [Farnell](#) and was most impressed with their free next day delivery.



Some of the part numbers had gone obsolete, mainly due to [ROHS](#), so I made the following substitutions :-

Description	Original	Substitute
Steel M5 Studding	517343	517409
Steel M3 Nuts	758796	8861250
Steel M3 Washers	149687	8861447
Steel 25mm M3 cap screws	100165	8838887

10mm PTFE rod was out of stock but I found a cheap source of 12mm rod on eBay at [Fantastic Plastic](#).

I also ordered a 5Kg reel of HDPE filament to get started with. It cost £85 including shipping. I plan to recycle milk bottles eventually but that will require a grinder. A four pint milk bottle weighs about 25g which makes them worth about 42p each. They must cost a lot less than that to make so the implication is that this stuff, sold as plastic welding rod, is overpriced.



The reel is a bit big and heavy to mount on the machine so I will probably have to re-spool it somehow.

It is a good job that I bought the filament before I made the extruder. The instructions specify to drill out the barrel to 3mm but my filament measures 3.2mm! I have ordered a 3.3mm drill from [www.toolfastdirect.co.uk](http://www.toolfastdirect.co.uk).

I also bought some nichrome wire to make the heater and some J-B Weld to attach it to the barrel and provide the electrical insulation and thermal coupling.



This stuff is rated up to 600°F. It is a departure from the original design which uses PTFE tape so it will be a bit experimental. I am hoping the thermal coupling will be good enough to allow me to use the resistance of the nichrome wire to measure the temperature rather than having a separate thermistor.

# It speaks!

Monday, 23rd April 2007 by Nophead

HydraRaptor just replied to ping, so that's PHY, MAC, ARP, IP and ICMP working.

```
Pinging 10.0.0.42 with 32 bytes of data:
```

```
Reply from 10.0.0.42: bytes=32 time=1ms TTL=128
```

```
Reply from 10.0.0.42: bytes=32 time<1ms TTL=128
```

```
Reply from 10.0.0.42: bytes=32 time<1ms TTL=128
```

```
Reply from 10.0.0.42: bytes=32 time<1ms TTL=128
```

```
Ping statistics for 10.0.0.42:
```

```
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
```

```
Approximate round trip times in milli-seconds:
```

```
    Minimum = 0ms, Maximum = 1ms, Average = 0ms
```

UDP next.

# It speaks, but my PC has its fingers in its ears

Monday, 23rd April 2007 by Nophead

I almost got UDP working this evening. I wrote a simple Python test script to send a "get status" command to HydraRaptor. Here it is :-

```
from socket import *

# Set the socket parameters
hydra = "10.0.0.42"
inPort = 21000
inAddr = (hydra,inPort)
outPort = 21001
outAddr = ("localhost",outPort)
buf = 1024

# Create sockets
sendSock = socket(AF_INET,SOCK_DGRAM)
recvSock = socket(AF_INET,SOCK_DGRAM)
recvSock.bind(outAddr)
recvSock.settimeout(2.0)

# Send a get status command
cmd = "\x12\x34\x56\x78\x00"
if(sendSock.sendto(cmd,inAddr)):
    print "Sending message ....."

# Receive the reply
try:
    data,addr = recvSock.recvfrom(buf)
    if data:
        print " Received message '", data, "'"
except:
    print "Read failed"

# Close sockets
recvSock.close()
sendSock.close()
```

HydraRaptor replies with its x,y,z coordinates and the number of steps remaining. The reply packet arrives at my PC which then sends an ICMP destination unreachable (port unreachable) message back. I have no idea why. netstat -ad shows :

```
UDP    shuttle:21001
```

```
***
```

```
2412
```

[Pythonwin.exe]

Which looks to me to show that the port is being listened to. I have tried turning my firewall off but that made no difference. I am sure the problem is at the PC end because Ethereal shows me that the packets are well formed. I have had enough for this evening. Any Python socket experts out there? I have never done sockets in Python before.

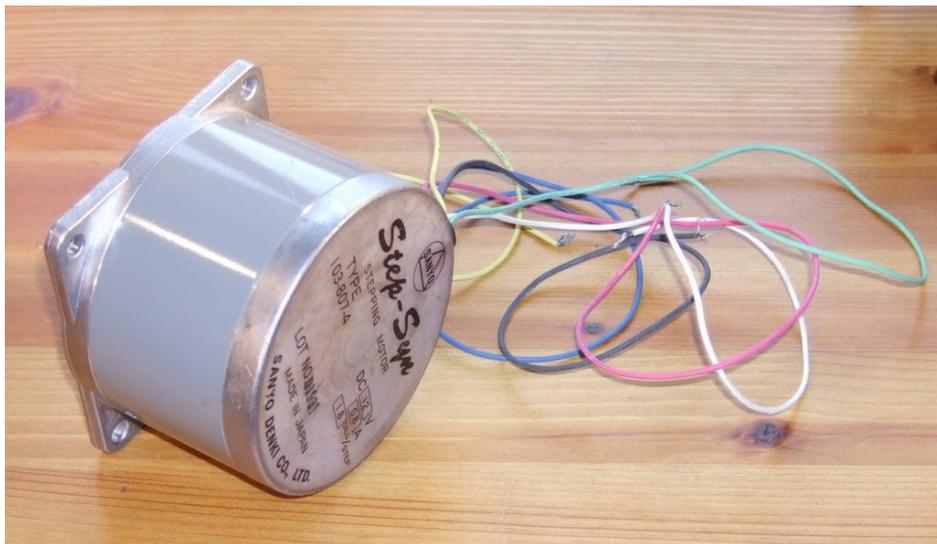
# Double chicken and egg

Monday, 23rd April 2007 by Nophead

My spiral saw arrived at the weekend. Although it was dispatched the day after I ordered it, it took another 17 days to get here from Yorkshire. For some reason Business Post could not find the address. Have they never heard of Google maps ?!

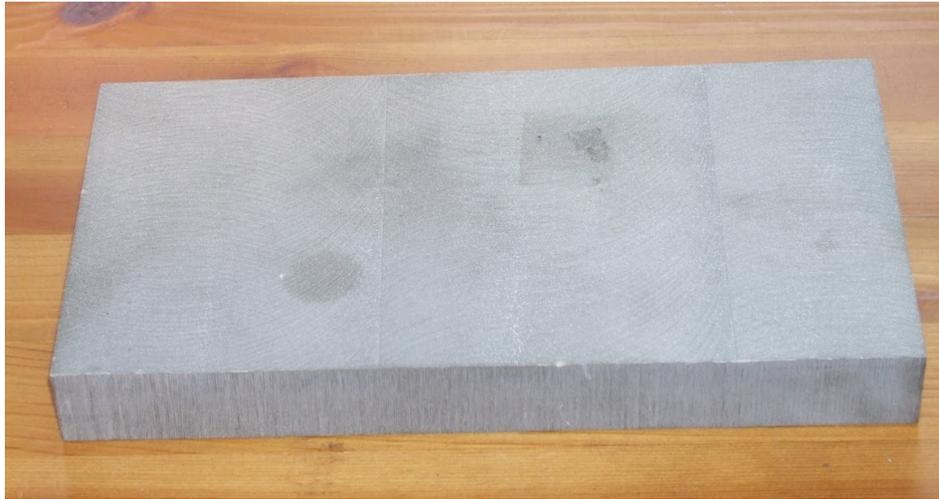


Although it was only cheap it does seem to have pretty solid bearings so looks promising for routing. At 600W and revving at 30000 RPM it should rip through most things. I just hope my z-axis motor is strong enough to lift it at 1.6Kg. If it can't then I may have to counter-balance it with a weight and a pulley or else use a bigger motor like this one for example.



I don't have any torque data for it but, at 85mm diameter, it looks beefy.

I plan to make the extruder body by milling this material.



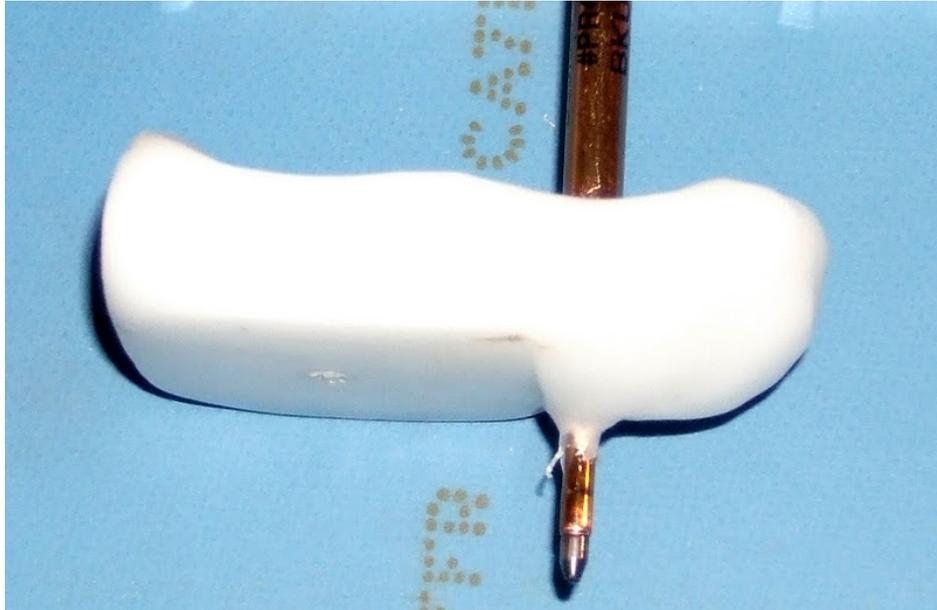
I don't know what it is but it seems very hard and rigid. My best guess is that it is some sort of epoxy type resin with possibly a metallic filler - it has a bit of a sparkle to it. I might be completely wrong though. Anybody know what it is?

The chicken and egg problem is that to make the extruder I need to use the router, but to make the router mountings I could do with using the extruder!

# My PolyMorph has morphed!

Tuesday, 24th April 2007 by Nophead

I now have HydraRaptor controlled by a Python script running on my PC. I decided to test its circle drawing ability in preparation for using it to mill a large hole in the block of material shown in the last post. When I came to refit the pen holder that I made a few weeks ago I noticed it was no longer a good fit. On closer examination it appears to have curled up a bit.



A bit disappointing because I don't like making things twice. Also it doesn't bode well for objects made by FDM, although this was cast rather than extruded.

# Microwaving PolyMorph

Wednesday, 25th April 2007 by Nophead

Following a discussion in the [RepRap](#) forums I decided to find out what happens if you microwave PolyMorph. I placed about 25g in a glass dish together with a mug of water in our 650W microwave oven.



I tried 30 seconds of defrost first which had very little effect. Next I tried 30 seconds of full power. That raised the temperature of the water to 40°C but had little effect on the PolyMorph. A further minute got the water to 60°C and the PolyMorph to 30°C. After another minute the water boiled and the PolyMorph got to 41°C. I replaced the water with cold and heated it for another 2 minutes. At that point the PolyMorph was at 80°C and most of it had melted.



I formed it into a ball and made a new pen holder. At the point where I took this photograph it was still too molten to support the pen.



It took quite a long time to set, longer than my first attempt using hot water. As I kept it pressed against the metal while it was setting it ended up a lot flatter. The result was not pretty because some of the unmelted granules are visible. Also the pen is welded in, whereas it was removable from the other one.



I must admit it looks almost as curved as the first one.



After drilling and bolting the holder to the metal plate the pen is held rigidly again but the holder

has shrunk so that the back is about 1mm away from the back of the plate. It is the front edge which locks it in position.

Conclusions: Well I wouldn't recommend microwaving as a way of melting PolyMorph because it is not even enough. The outer edge, where it is in contact with the glass dish, is a lot cooler. Also it does not absorb microwaves anything like as well as water does.

I think most of the shrinking and curling occurs when it first cools down but I can't explain why the first one can no longer be locked in place. Maybe there is some further shrinkage over the long term.

# Ever decreasing circles

Saturday, 28th April 2007 by Nophead

I wrote some test code in Python to check that my firmware was working properly. This turned out to be incredibly easy using the socket and struct modules. I have not written a lot of Python before but it never ceases to amaze me how much more productive it is compared to C++. Handling the Ethernet UDP comms required only a few lines of code. Here are extracts from the constructor and destructor :-

```
from socket import *
from struct import *

class Hydra:
    def __init__(self, ip_addr):
        # Create sockets
        self.sendSock = socket(AF_INET, SOCK_DGRAM)
        self.sendAddr = (ip_addr, 21000)

        self.recvSock = socket(AF_INET, SOCK_DGRAM)
        self.recvSock.bind(("", 21001))
        self.recvSock.settimeout(0.1)

    def __del__(self):
        # Close sockets
        self.recvSock.close()
        self.sendSock.close()
```

Below is the code that sends a command and receives the reply. UDP packets are not guaranteed to arrive at their destination and if they do they are not guaranteed to arrive in the same order they were sent in, although on a small single segment LAN they generally do. Packets are protected by CRCs and checksums so if you do receive a packet you can be pretty sure it is not corrupt.

To make a reliable protocol timeouts, retries and packet sequence numbers are required. I also added a 4 byte magic number at the start of each packet just to make sure a stray packet from a rogue application or the Web could not cause HydraRaptor to lose the plot.

```
def do_cmd(self, cmd):
    tries = 3
    while tries:
        self.sendSock.sendto('\x12\x34\x56\x78' + cmd, self.sendAddr)
        try:
            data, addr = self.recvSock.recvfrom(1024)
            return data
        except timeout:
```

```

        print "read failed"

        tries = tries - 1

    raise 'comms failed'

```

Here is the code to wait for the machine to be ready and then instruct it to go to to a 3D position.

```

def get_status(self):

    return unpack('>hhhhBB', self.do_cmd('\x00\x00'))

def goto_xyz(self,pos,delay):

    while 1:

        a, b, c, steps, seq, ready = self.get_status()

        if steps == 0 and ready:

            break

        seq = (seq + 1) & 255

        self.do_cmd(pack('>BBhhhh', self.goto_xyz_cmd, seq, pos[0], pos[1], pos[2], delay))

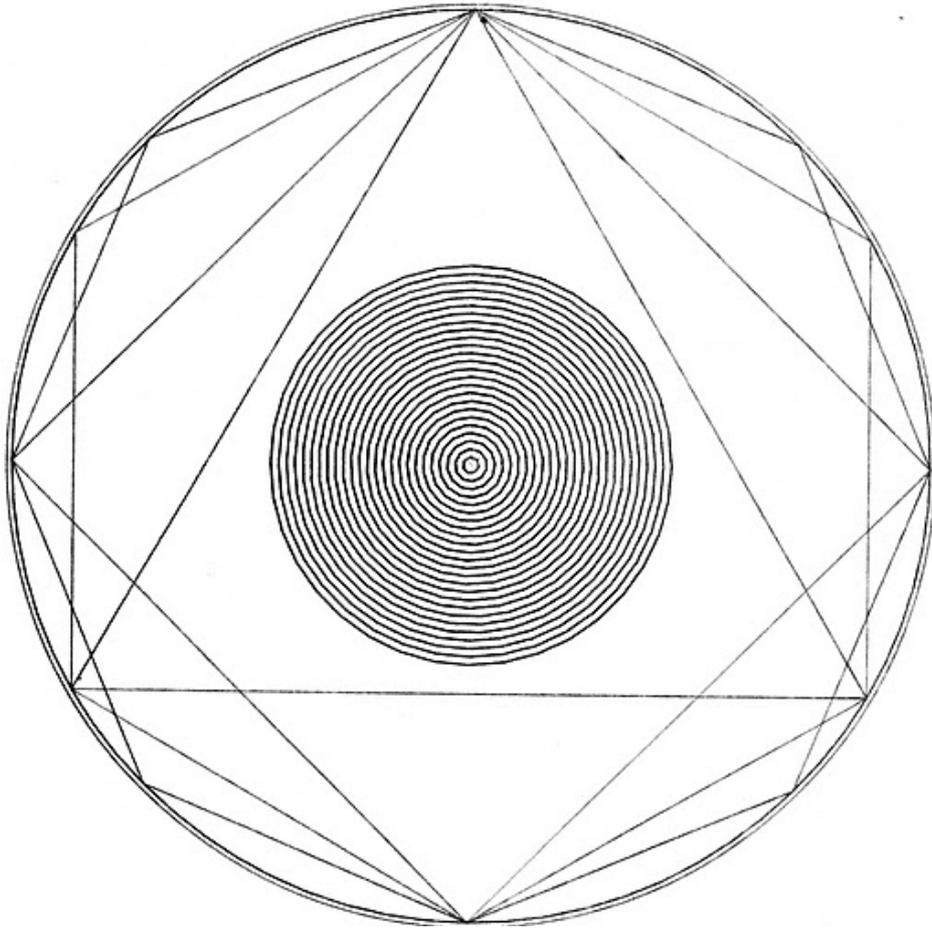
```

Notice how easy it is to marshal and unmarshal packets using the struct module. The big endian to little endian conversion is handled simply by putting a > sign at the start of the format string.

Below are some test patterns. The 25 circles in the centre are 1 - 25mm radius and are drawn with the minimum number of line segments to keep within 0.05mm accuracy. This is calculated with the formula

$$/ \text{acos}((r - 0.05) / (r + 0.05))$$

The outer circle is made with 360 line segments.



Not only can I now drive HydraRaptor from a script but I can also interact directly with it via the command line:

```
>>> hydra = Hydra("10.0.0.42")
>>> print hydra
At (9944,11943,400) steps = 0
>>> hydra.goto_xyz((0,0,0),1000)
>>> print hydra
At (3310,3976,133) steps = 3976
>>> print hydra
At (0,0,0) steps = 0
>>>
```

I noticed that although the Z axis is repeatable in the short term the distance to the paper varied by about 0.1mm over a two day period. I expect this is due to the MDF expanding and contracting slightly. I plan to make a tool height sensor mounted on the XY table to make it easy to switch tools. This should also compensate for the wood changes.

The next thing to do is use my existing milling setup to make some motor mounts to make an improved milling machine. To do this I will extend my Python script to allow me to define an outline as a list of lines and arcs and then mill around it.

I will then try to make the RepRap FDM extruder with the improved milling machine.

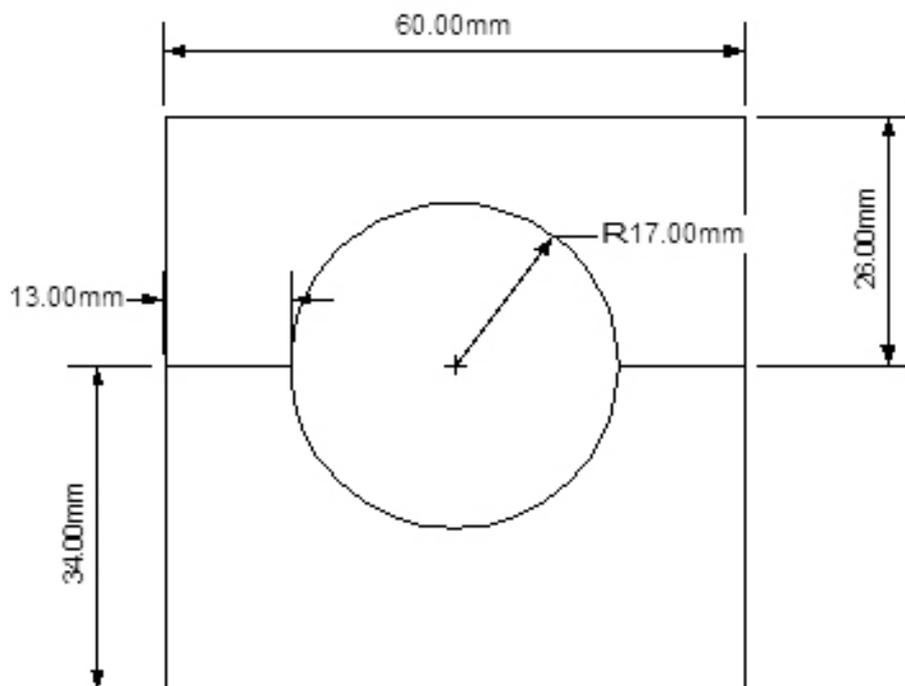
# On the right path

Tuesday, 1st May 2007 by Nophead

Having tried a cheap mini drill as a router and found it lacking I ordered a cheap laminate trimmer to try instead. While I was waiting for it to arrive I remembered that I had inherited a Minicraft drill from my aunt.



To my surprise this seems quite promising. The bearing is solid and it revs to 20000 RPM without too much noise. It also has the advantage that it is small and light so is suited to a multi-headed machine. I decided to see if I could use the first drill to mill a mount for the new one out of a block of hard plastic. I designed a simple two part clamp using Visio.



I represented the outline of the parts using a couple of Python lists.

```
bottom_clamp = [Line(0,34), Line(13,34), Arc(30,34,47,34), Line(60,34), Line(60,0), Line(0,0)]
top_clamp = [Line(0,26), Line(60,26), Line(60,0), Line(47,0), Arc(30,0,13,0), Line(0,0)]
```

Line and Arc are simple classes with a do method which instructs HydraRaptor to move along the segment. E.g.

```
class Line:
    def __init__(self,x,y):
        self.end = (x,y)

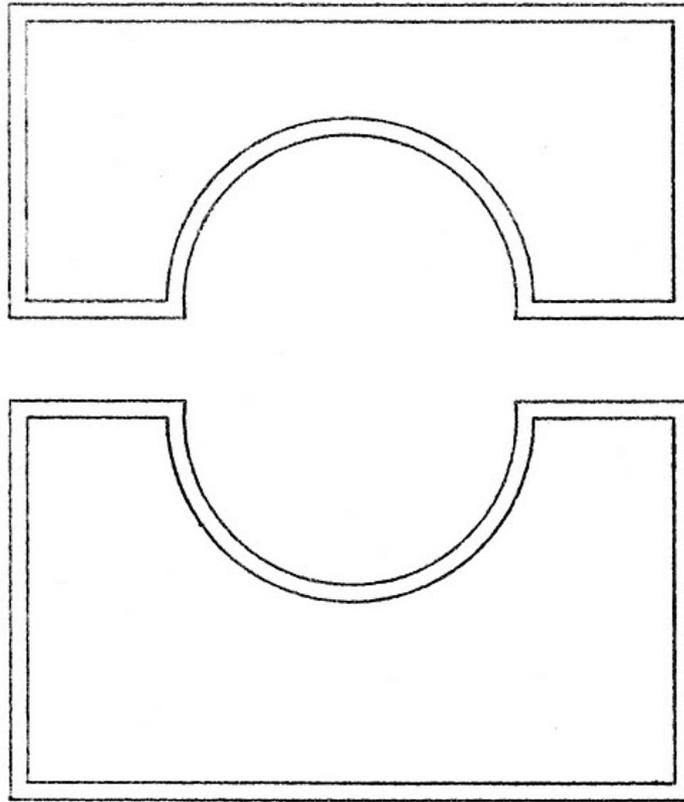
    def do(self,hydra):
        hydra.feedto_xy(self.end)
```

It was then trivial to get HydraRaptor to draw the outlines with a pen using a for loop :-

```
for seg in outline:
    seg.do(hydra)
```

However in order to be able to mill it out I need to create a tool path which is offset by the radius of the bit. This is a little harder than it sounds. It is easy enough to offset a line at right angles to its direction but then the ends no longer meet. A new intersection point has to be calculated and a different calculation is required for each possible pair of segment types. I decided to prove to myself that I could still do O-level maths and worked out the equations from scratch. A quick Google afterwards verified that they were correct before coding them up. Here is the "line to line" case <http://local.wasp.uwa.edu.au/~pbourke/geometry/lineline2d/> and here is "line to arc" <http://local.wasp.uwa.edu.au/~pbourke/geometry/sphereline/>. The trick is to represent lines with a pair of parametric equations rather than simply  $y = a + bx$  to avoid having special cases for verticals.

Having done that I got HydraRaptor to draw the tool paths with the pen. Here is the result :-



The next step is to actually mill it. I am not sure how I am going to hold the plastic block down yet. I think I will try double sided tape and if that fails contact glue.

# More trouble at' mill

Wednesday, 2nd May 2007 by Nophead

Well things did not quite go to plan. The first problem was that most of my milling bits have ends that are smaller than the top of their shafts so they cannot go very deep. The only exception is a 1/8th inch end mill that came as part of my PCB routing set. It is intended for routing PCB board outlines. The problem was that my first drill did not have a collet big enough to take it. The Minicraft replacement has a three jaw chuck which will. So plan B, I fitted the Minicraft drill into the bottom MDF mount intended for my other drill. Rather than tackle the big block of hard plastic I thought I would try it out on a sheet of scrap polystyrene first. I stuck this down with double sided sticky tape.



I started with a feed rate of 4mm per second. This was far too high as it stalled the drill. I dropped down to 1mm per second and then to 0.5mm. At this point it seemed to be able to handle the cutting but it kept snatching horribly. I dropped down to 0.1mm per second which took ages but it still snatched. I only got as far as the first corner before I aborted. You can see that after the first 15mm it no longer goes right through the plastic. This is because I did not tighten the chuck enough and the bit slipped.

I might be wrong but I think the snatching is due to the set up not being rigid enough. I had already identified that as a weak point and the new motor mount was aimed at improving it. The first drill

was supported at both ends but this one is too short so it needs a much stiffer mount, which is what I was trying to make! Perhaps the end mill bit is not suitable for styrene, or perhaps styrene is not very machinable, or perhaps the RPM is too high, or too low. Can you tell I am a bit out of my depth here?

One thing I can do to improve stiffness is to replace the 2mm aluminium plate with the 6mm slab I already bought for the job. I was putting that off until I got the new mount so as not to have to drill two sets of holes in it.

Another thing I might try is to make a top mount out of PolyMorph.

# Heavy metalwork

Thursday, 3rd May 2007 by Nophead

Just spent all evening making a 150mm cut across a 6mm sheet of aluminium. Not fun I can tell you. I used a jig saw and got through three HSS blades. After the first blade I tried using paraffin as a lubricant and it made a big improvement. Holding the saw for about an hour and a half on and off was horrendous because of the the vibration. It was all the more annoying because I paid over the odds on eBay to get a piece exactly the right size but the description changed during the auction. There was even a line already marked where I had to cut it.



Ironically, after finding it so hard to saw, I managed to clean up the edges on my bench sander demonstrating how soft aluminium is. I probably needed a saw with coarser teeth. Perhaps I should have tried a wood blade but I think that would have been too coarse.



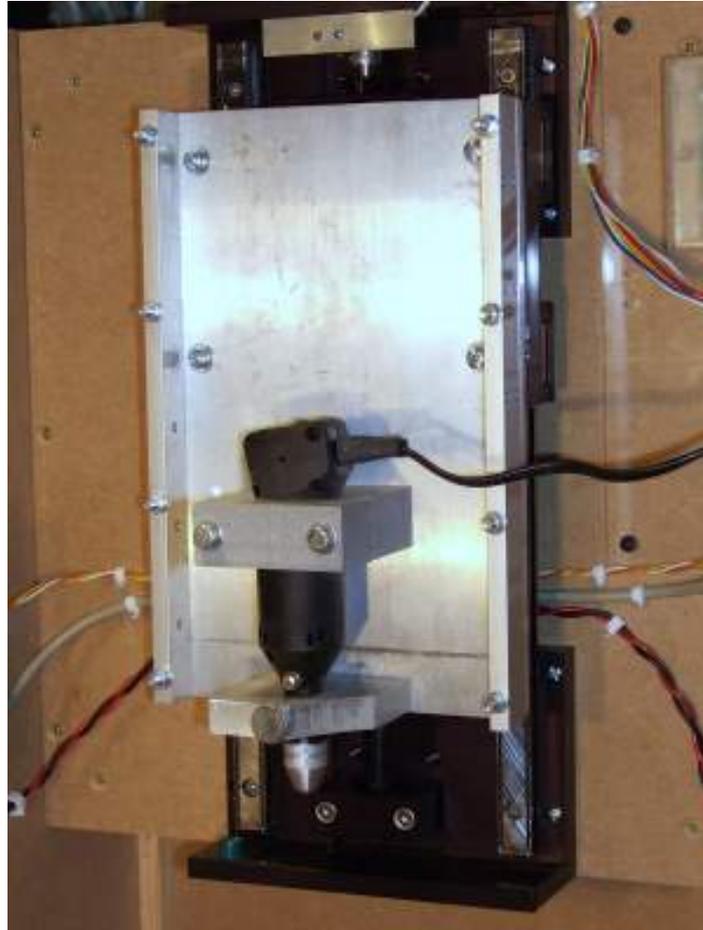
Drilling next: I hope that goes a bit better. I will definitely use paraffin again. I am not sure where I got that tip from, it might have been my Dad.

PS: Found a better way of blogging my pictures so now you can click on them for a higher resolution. If anybody wants to see a better version of a previously posted image let me know and I will upgrade it.

# Stiffening up

Monday, 7th May 2007 by Nophead

Having severely underestimated how stiff a milling machine needs to be several times, I decided to make a solid job with my next attempt. Two days of metal (and plastic) work later here it is :-

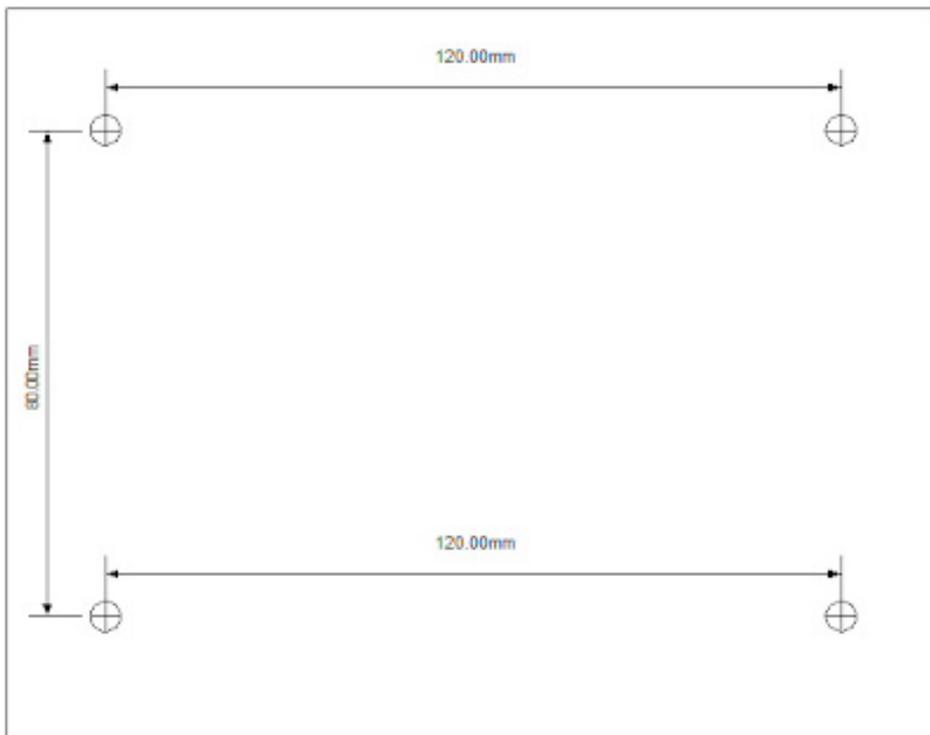


The back plate is 6mm aluminium sheet strengthened up with a couple of 8mm by 20mm aluminium rails. The bottom mount is 13mm thick aluminium and the top mount is the mystery metallic plastic composite I mentioned earlier. I am still none the wiser as to what it is but I can say that it is light, very rigid and machines very nicely. Drilling makes perfect holes with no burr. The only thing I don't like about it is that it gives off a very fine dust. I expect that goes hand in hand with machining well.

The end result is solid as a rock. I think the only weak point now is the MDF frame but as I only want to do light milling I hope to get a way with it.

I have improved my metalwork techniques since the previous attempt. It is actually more difficult that one would imagine to drill accurate holes. Here is the method I use :-

1. Make a template in Visio with the outline of the work piece and cross hairs where the holes should be.



2. Print it out 1:1 and cut round the outline.
3. Place it over the work piece and centre punch where the cross hairs are with an automatic punch.
4. Drill pilot holes at 1.5mm, using a drill press.
5. Open the holes out 2 or 3mm at a time by using successively larger drills until the target size is reached.
6. De burr with a larger drill.

When drilling aluminium you need to keep the drill speed low, especially with larger holes. A drill with continuously variable speed is handy.

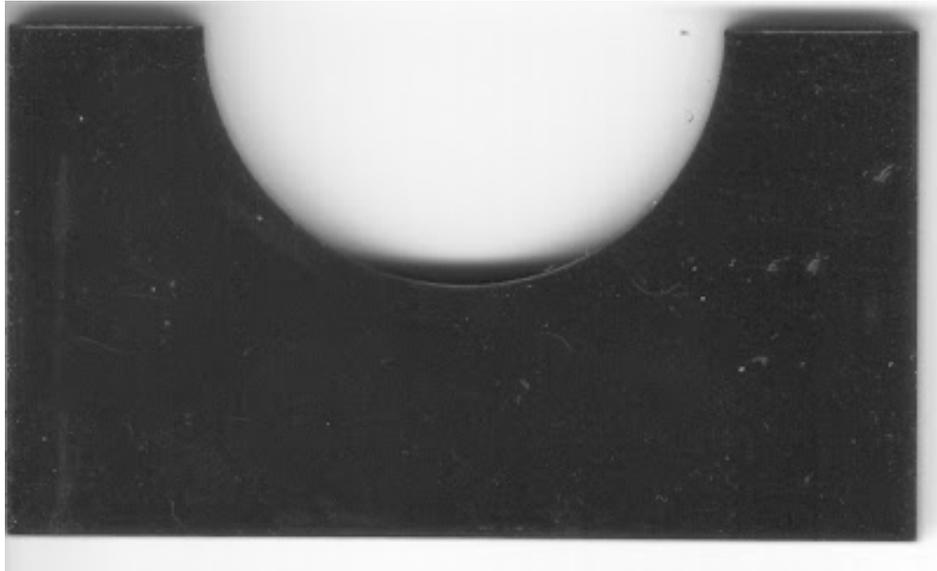
If the going seems to suddenly get tougher, for no apparent reason, then it generally means the bit has got clogged. Back out, switch off and pick the swarf out of the flutes. Using paraffin to lubricate helps to prevent this.

The next thing is to try milling again although I no longer need the drill mount I was trying to make earlier as I have had to make it by hand.

# Successful milling

Tuesday, 8th May 2007 by Nophead

The new metalwork did the trick. It completely solved the snatching problem I had previously. I managed to mill this test shape out of 2.5mm polystyrene, at least that is what I thought it was. I found a site: [www.tempatron.co.uk/weld\\_rods.htm](http://www.tempatron.co.uk/weld_rods.htm) which describes how to identify plastic by setting fire to it and the closest match is ABS, so it may in fact be ABS.



As you can see it has nice clean edges and it measures 34.07mm by 60.02mm by my cheap electronic calipers so is pretty accurate.

Getting the feed rate and cut depth right took a few attempts. The problem was that the plastic kept melting as you can see here :-



I found that with a cut depth of 0.5mm I could only feed at about 0.2mm per second to prevent

melting. Reducing the cut depth to 0.1mm allowed me to increase the feed to 10mm per second which is ten times more productive. I probably could have pushed it further but I am not particularly interested in making anything from this material. Here is a video of the test :-

I now have a small but highly accurate CNC milling machine. A few improvements are definitely needed :-

1. Dust extraction!
2. Tool height detector
3. Spindle motor control and stall detect

# Dust bustin'

Sunday, 13th May 2007 by Nophead

I decided to tackle dust extraction as my first attempt at milling plastic made a right mess as you can see below in the video. The problem with taking a very fine cut is that you get very fine chips. These defy gravity and even stick to the underside of the things, presumably due to static.

My first idea was to enclose the tool in a pipe which reaches down to just above the workpiece. A vacuum feed then needs to come in from the side. I bought a small vacuum cleaner for the bargain price of £17.42.



It seems a bit ridiculous to use 1300W to remove dust from a machine that takes less than 5W to make it but I can't think of a better solution. I might be able to reduce the power with a motor controller if I find I have suction to spare. If not I can always put the air conditioning on to waste even more power.

I tried using a reducer and a small diameter pipe but the reduction in suction was too great so I decided to keep the full bore right to the workpiece.



I started with a small waste pipe T-junction and cut most of it away to leave the shape I wanted.



I then used HydraRaptor to mill a ring to reduce the top pipe diameter to the size of the drill shaft. This will also be the means of attaching it to the underside of the bottom motor mount. I practiced first on a piece of scrap 2.5mm polystyrene before making the final piece in 5mm ABS. You can see that it was a good idea to practise on the scrap first as I made two really stupid mistakes. The first one was to cut the outer circle first! The second one was to offset by just over the diameter of the ring to do a second one. I forgot to add the diameter of the tool! The ring on the right is the finished article. I was able to increase the feed rate to 20mm / second, sticking with the 0.1mm cut depth.

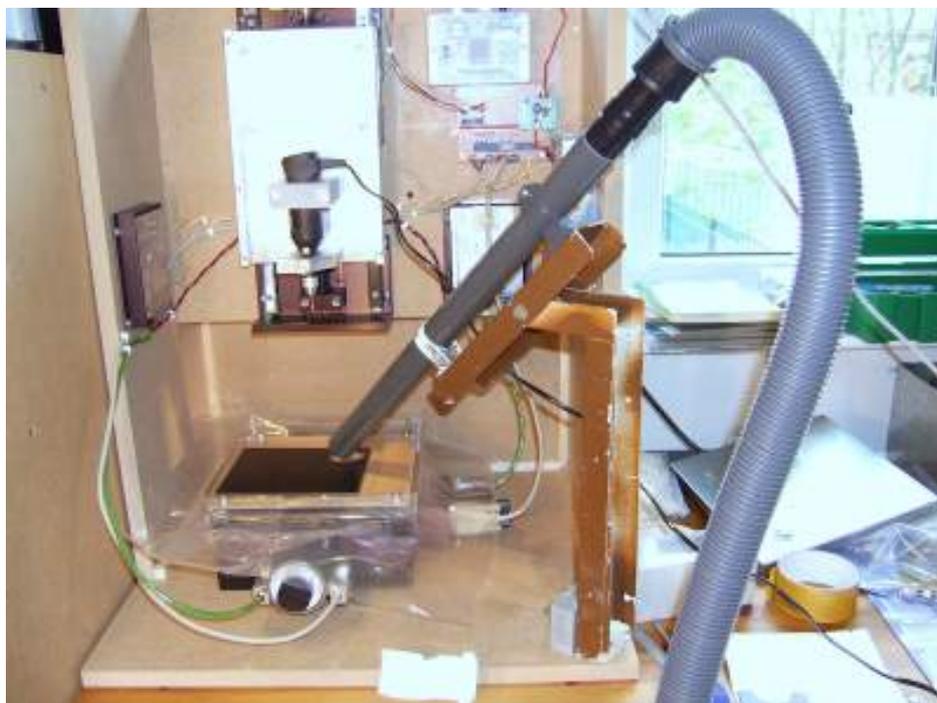


Here is the finished article :-



This is a bit of a landmark as it is the first useful item that HydraRaptor has made. Not very RepRap as it is a subtractive rather than additive process, but it is a part of itself.

While HydraRaptor was making the ring I held the vacuum cleaner nozzle close to the work piece. It was very effective at removing the dust even though there was only a very poor seal. It has the advantage that it does not need to move with the z-axis. It only needs to be suspended in a fixed position just above the work piece. I decide to abandon the piece I had just made and go for a bracket that can hold the nozzle at a fixed but adjustable height. I made this contraption out of a bracket that was formally used to hang a microwave oven on a wall.



This method works well for plastic but I may have to revert back to plan A when milling copper as the chips are a lot heavier.

BTW, I came across a much better plastic identification flow chart, than I mentioned last time, in the RepRap forums: [www.texloc.com/ztextonly/clplasticid.htm](http://www.texloc.com/ztextonly/clplasticid.htm).

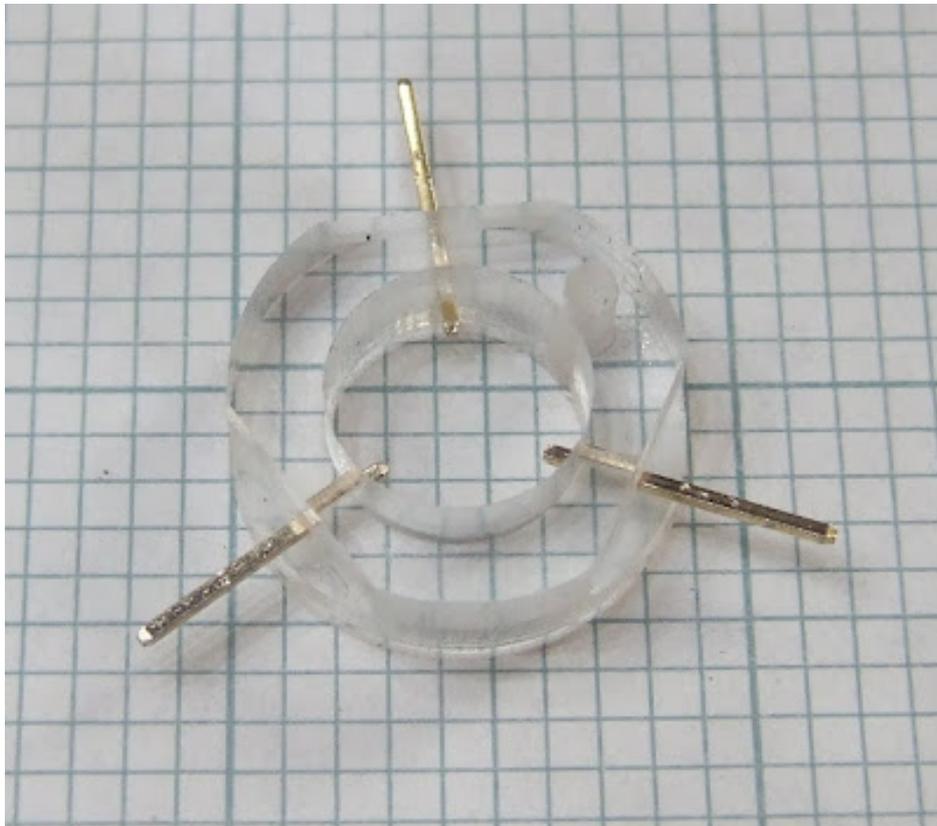
The next thing I intend to tackle is a tool height sensor as it is a pain getting  $Z = 0$  to be exactly where the tool meets the sacrificial base material each time a tool is changed.

# How long is your tool?

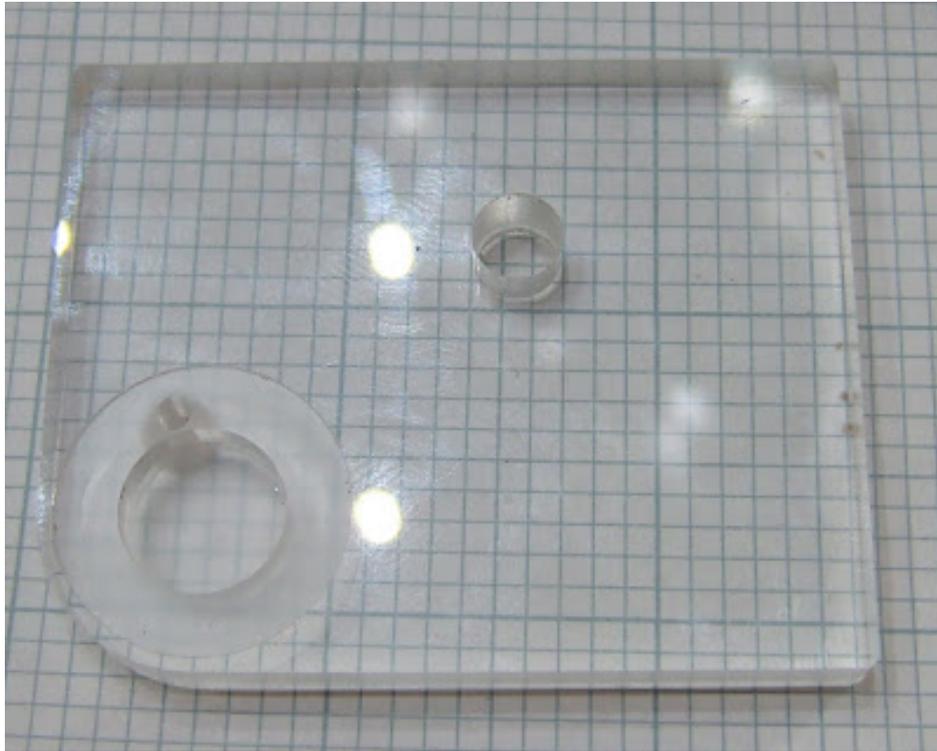
Friday, 18th May 2007 by Nophead

I decided to make a tool height sensor as a high priority because finding the  $Z = 0$  setting manually is time consuming and risks breaking expensive milling / drill bits. I got my design inspiration from [The "One Penny" Touch Probe](#). I basically turned it upside down. My plan was to have a spring loaded disk pressing upwards against three contacts. Any movement of the disk downwards must break at least one connection. Note that the circuit in the aforementioned article is a little bit more complicated than it needs to be. Rather than use a three input OR gate you can just connect one of the contacts to ground and use a two input OR gate. That also dispenses with a connection to the disk.

Things went well to start with. I milled a ring with three flats on it out of 6mm [Perspex](#). I drilled into the flats and inserted three gold plated pins extracted from a 0.1" header.



I then milled a base which bolts into one corner of the tray on top of my XY table. It has a circular recess to locate the base of the contact ring and a blind hole to house the spring. The corners are all radiused.



The small screw hole in both pieces was drilled manually with a small drill press, the rest was all done by Python script driving HydraRaptor with a 1/8 inch end mill. Here is a video of the ring being made, the flats were added by a third pass :-

The perspex milling went remarkably well at 10 mm per second feed rate, 0.1mm cut. I glued the sheet down onto the sacrificial base (floor laminate) using plasti-kote stencil mount. This worked well but I had to leave it 24 hours to dry because it was pretty much sealed between the two sheets. I removed it from the workpiece afterwards with Stain Slayer tar and grease remover.

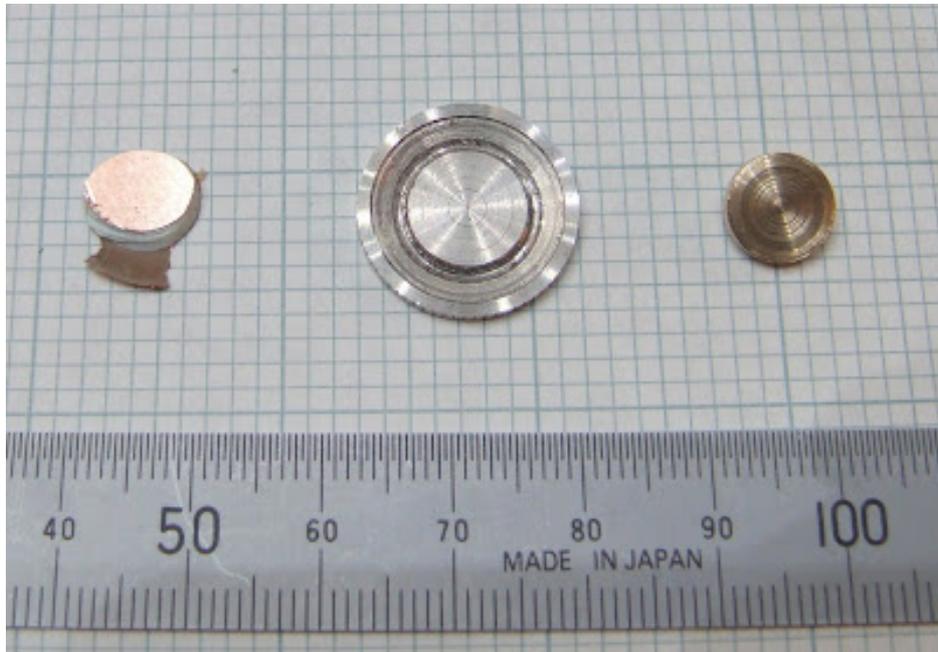
The only slight defect was that the parts are slightly undersized for most of their height, but a bit bigger at the bottom. At first I thought that the tool wasn't plunging deep enough into the base material. I tried increasing that with no effect, so the explanation I came up with is that the tool gets a bit clogged with perspex and that rubs against the work piece making it slightly undersized and gives it a polished appearance higher up the edge.

Flushed with success, I thought making a conductive disk would be a doddle but it turned out much harder than I thought. My first idea was to mill a 9.5 mm disk out of PCB material. I stuck that down with stencil mount but I only left it to dry a few hours. It came lose while milling, creating an egg shape.

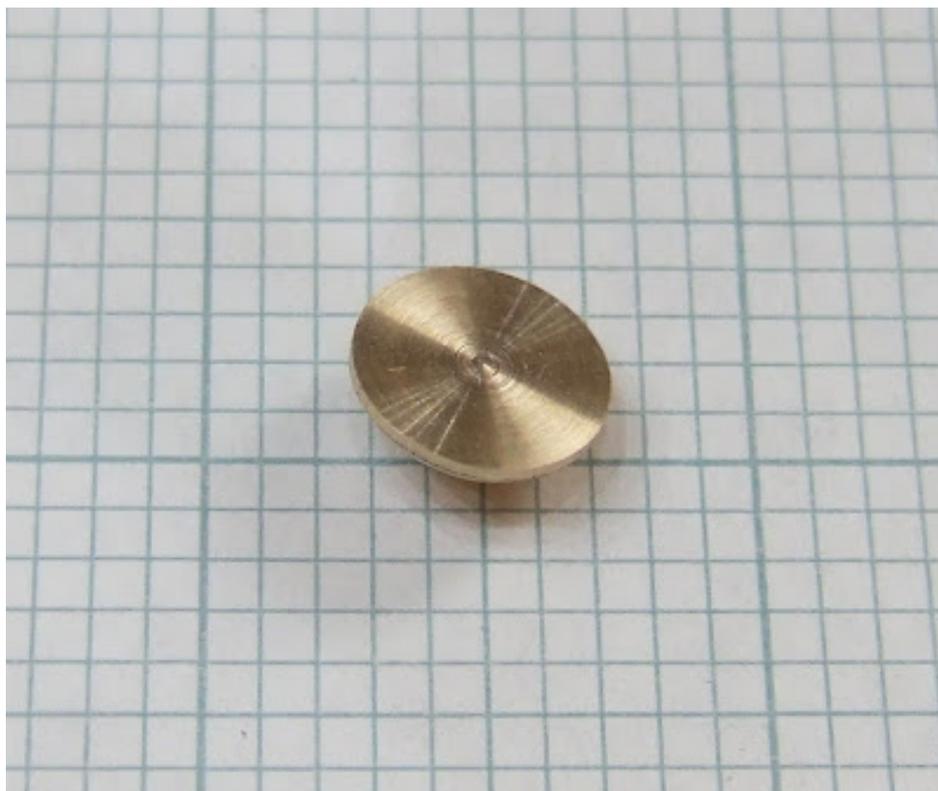
My second idea was to turn down a cupro-nickel disk on my watchmaker's lathe. I can't say where this disk came from but I can say that it cost exactly 5p. My plan was to hold it by its outside edge in a chuck and plunge a tool into the face to get the correct diameter. After an evening of trying every tool I had and shaking the lathe apart I realised that is not an operation you can do on a lathe. Normally you cut across a face or along the length of the piece. In that case only the leading

edge of the tool is actually removing metal. If you try to plunge a tool into the face of the workpiece the whole of the tool width is trying to cut. It just digs in and stalls the lathe. Perhaps a very thin tool might work but I don't have one. The only way to reduce the diameter with the lathe is to turn it from the outside but then there is nothing to hold it by.

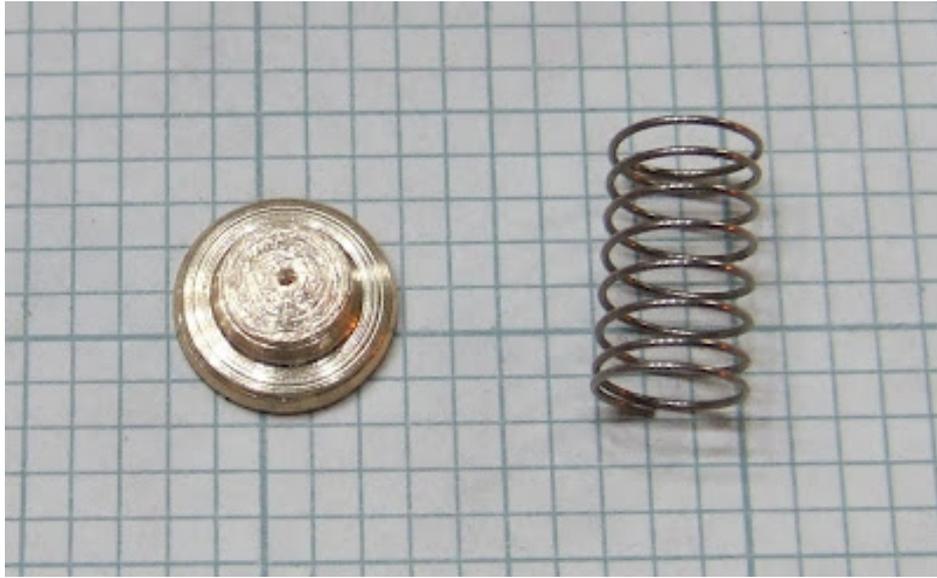
My third idea was to turn down a bit of 10mm brass bar and then cut the end off to make a thin disk. This worked at the second attempt, after I had improved my lathe skills a bit. Here are the three rejects :-



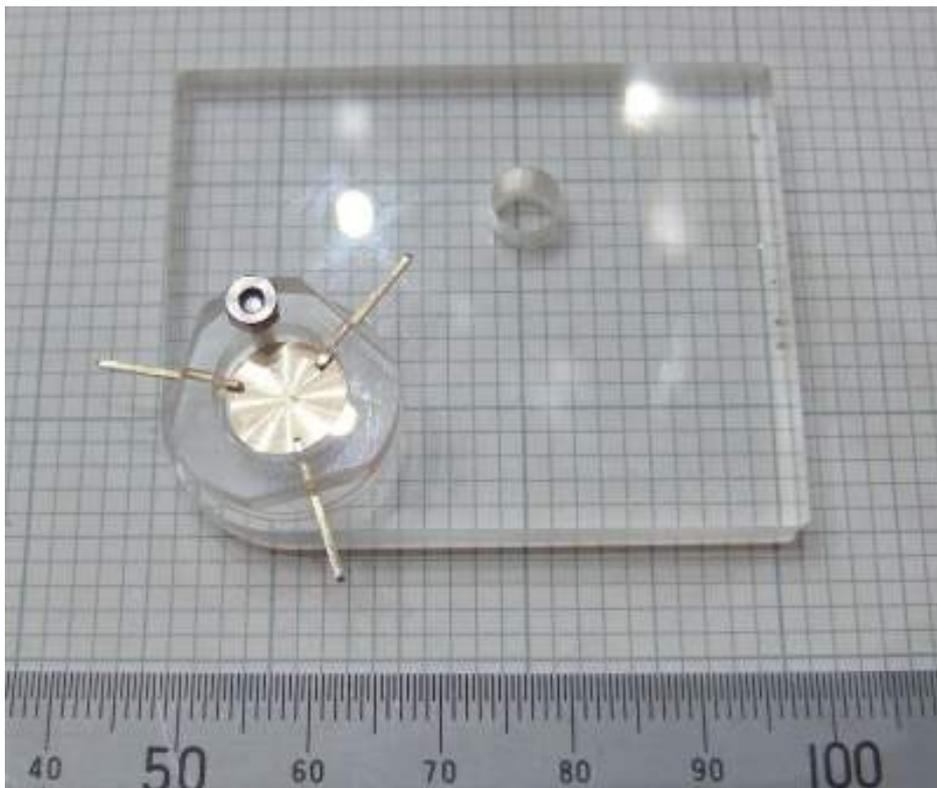
And here is the one that worked :-



I made a 5mm stalk on the back to locate the spring :-



And here is the assembled sensor :-



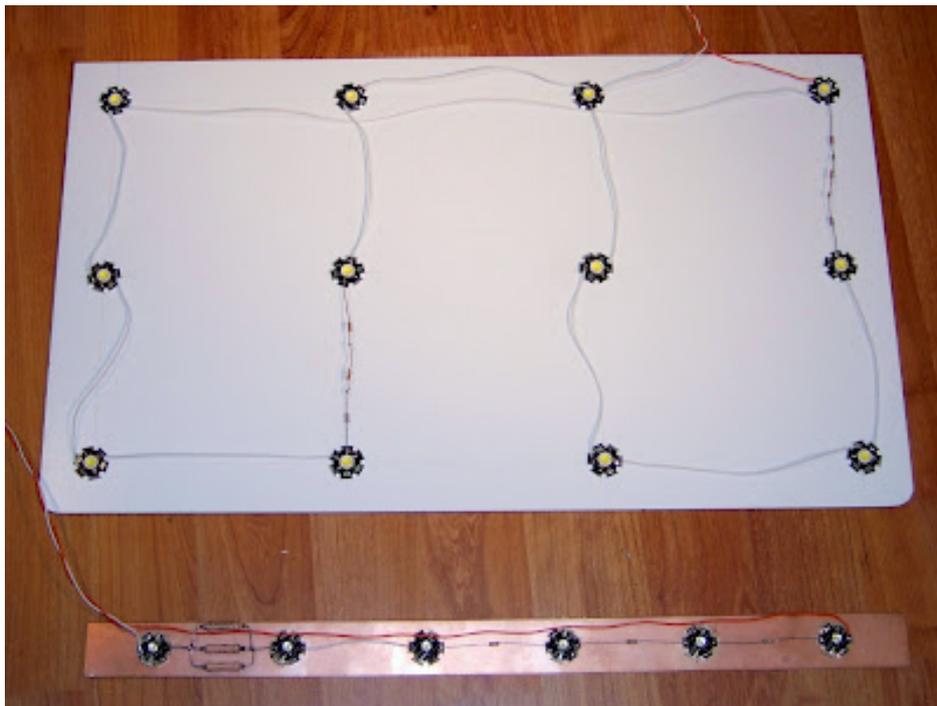
To my amazement when I metered it out there was no connection between the contacts. How could brass pressed against gold not make contact? After close inspection I realised that the disk was resting on small Perspex burrs where I had drilled the holes for the pins. I removed the pins and scraped off the burr with a pen knife and that fixed it.

Tomorrow I will wire it up and see how it performs. The only thing that worries me is that the brass might tarnish with time. At least it will fail safe if it does. I have a small gold watch case that I can cut a disk from if need be.

# Let there be light

Sunday, 20th May 2007 by Nophead

Taking close up video footage requires quite a lot of light because the maximum exposure is limited by the frame rate and zooming in wastes a lot of the light hitting the lens. I have previously been using a random collection of incandescent spot lights totalling about 200w. These gave an overly warm white balance with my camera, a Fuji Finepix 900, plus they tended to get in the way and gave off a lot of heat. I decided to try LED lighting as that seems to be the future. I suspended twelve 1W white LEDs over the top of the machine on a sheet of aluminium laminate plus another six on a strip of copper PCB laminate under the box that supports the Z-axis.



The LEDs were wired in groups of six in series and connected to the 24V supply with a small series resistor. I adjusted these to get about 300ma. A constant current source would have been better but I didn't have any suitable medium power transistors to hand and the supply is well regulated.

Here is what they look like in the machine viewed from below, they are not visible with the normal camera angle from above.



They seem to be bright enough for shooting video and they are only using 18W, 10 times less than my spot lights. If you compare my second video with the first you can see the difference although I didn't have the bottom six installed at that point.

# Tooled up

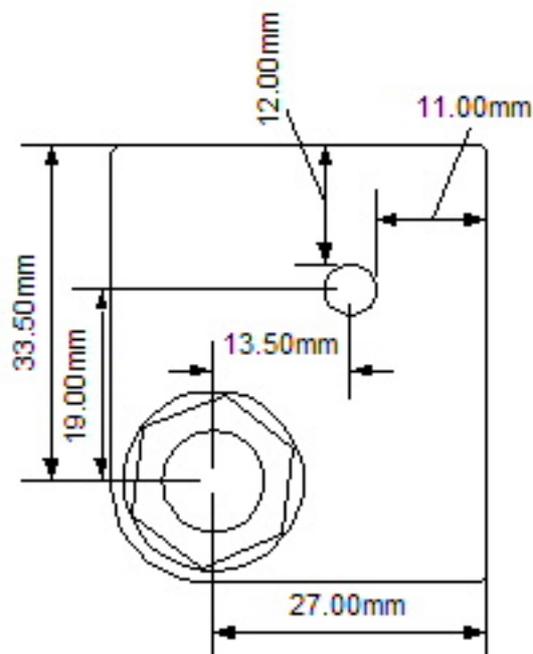
Saturday, 26th May 2007 by Nophead

I wired up and tested the tool height sensor that I made last week and it worked fine. It gave consistent and repeatable results. Rather than use an OR gate I just connected two of the pins to two inputs of my micro and did the OR in software. I configured the micro to have internal pull downs and I connected the third pin of the sensor to 3.3V via a current limiting resistor. This configuration allows for the tool to be connected to ground, in which case either the tool touching the disk or any of the three contacts being broken will take at least one of the inputs low.

The software just plunges the tool into the sensor at full speed. As soon as one of the inputs goes low it backs up 1 mm and then descends slowly until it breaks the connection again.

There was only one small problem ... I made it for the wrong corner of my XY table! Having it on the right meant that the vacuum pipe had to clear it so could not be as close to the workpiece as it could otherwise be. No problem, I just got HydraRaptor to make another base for the left hand corner. I designed the part in Visio and then manually made a Python script to mill it. At some point I need to find a free CAD / CAM program for things like this.

Here is the drawing :-



This is what the script looks like :-

```
from Hydra import *  
from Arc import *  
from Tool import *
```

```

from Line import *

hydra = Hydra("10.0.0.42")
top = 6.1
base = -0.3
hydra.work_origin = (-50,0)
hydra.work_height = top
hydra.measure_tool(end_mill)
hydra.tool = end_mill

tr = end_mill.radius

# recess
hydra.drill((0,0), 18.0, top, 5.6)
hydra.drill((0,0), 15.0, top, 5.6)

# spring well
hydra.drill((0,0), 10.0, top, 3.0)
hydra.drill((0,0), 2 * tr, top, 3.0)
hydra.drill((0,0), 7.0, 3.0, 1.0)
hydra.drill((0,0), 2 * tr, 3.0, 1.0)

# screw hole
hydra.drill((13.5,19), 5.0, top, base)

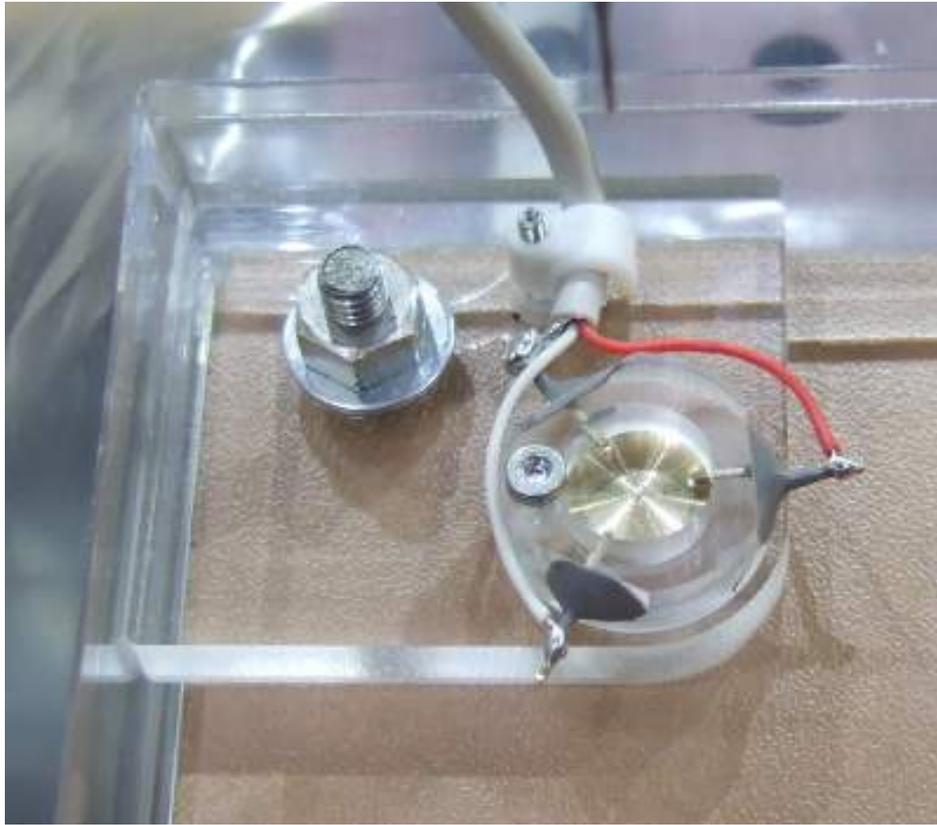
# outline
outline = [Line(-10,32.5), Arc(-9,32.5,-9,33.5,-1), Line(26,33.5), Arc(26,32.5,27,32.5,-1),
           Line(27,-9), Arc(26,-9,26,-10,-1), Line(0,-10), Arc(0,0,-10,0,-1)]

hydra.mill(outline, top , base)

del hydra

```

And here it is installed :-



You can see that I used JB Weld to glue the pins in. I did that to stop them moving when I soldered the wires on, as Perspex melts very easily.

Below is a video of the new base being made. You can see the right handed version of the tool sensor being used at the beginning. I upped the feed rate to 15mm per second with no problems. Even so it took more than 15 minutes to make the piece so I have speeded up the video by a factor of two.

Obviously it is important to switch the spindle motor off when measuring the tool! At the moment I am doing this manually. I forgot once but I got away with it because it measures so quickly. The next job is to put the motor under software control.

# Underpowered

Wednesday, 30th May 2007 by Nophead

I have done quite a bit of milling with my Minicraft drill attached to HydraRaptor. I always considered it a bit underpowered for the job but it mills plastic and copper clad board reasonably well. Recently I started using it for drilling plastic. The first thing I drilled was 6mm Perspex. I programmed a pecking action to avoid the drill clogging as Perspex tends to melt when it is drilled at high speed. Again this worked reasonably well. The next thing I tried was drilling 25mm metal loaded resin. No matter how slowly I went I could not stop the drill from stalling once it got to a certain depth.

I decided the only way to solve the problem was to monitor the drill speed, detect when it was about to stall and automatically back off until it speeded up again. To this end I started investigating ways to monitor the speed. Off the top of my head I came up with four alternatives :-

1. Monitor the current, because it increases as the speed reduces.
2. Turn it off occasionally and monitor the generated voltage.
3. Measure the frequency of the commutation noise.
4. Put a black spot on the chuck and use a reflective opto detector to count shaft revolutions.

I attached the drill to a 12V switch mode PSU in order to take some voltage and current measurements and look at the current waveform on a scope. To my surprise the drill went much faster on the 12V PSU. The PSU that came with it is labelled 11.5V 400ma 4.6W but when loaded by the drill it was only giving about 8V. Then I looked at the drill and saw it was labelled 12V 40W. A bit of a mismatch! When driven from 12V it takes about one amp with no load. No wonder it was stalling so easily. It also explained why when it does stall it does not seem to care. Most drills start smoking pretty quickly if you stall them.

So it looks like the drill is ten times more powerful than I thought. The only problem is that it could do with some speed control as it goes a bit fast for plastic when running from 12V.

So now my next task is to tame it with PWM and monitor the speed somehow. I also want to control the vacuum cleaner with software as I am too lazy to switch it on and off.

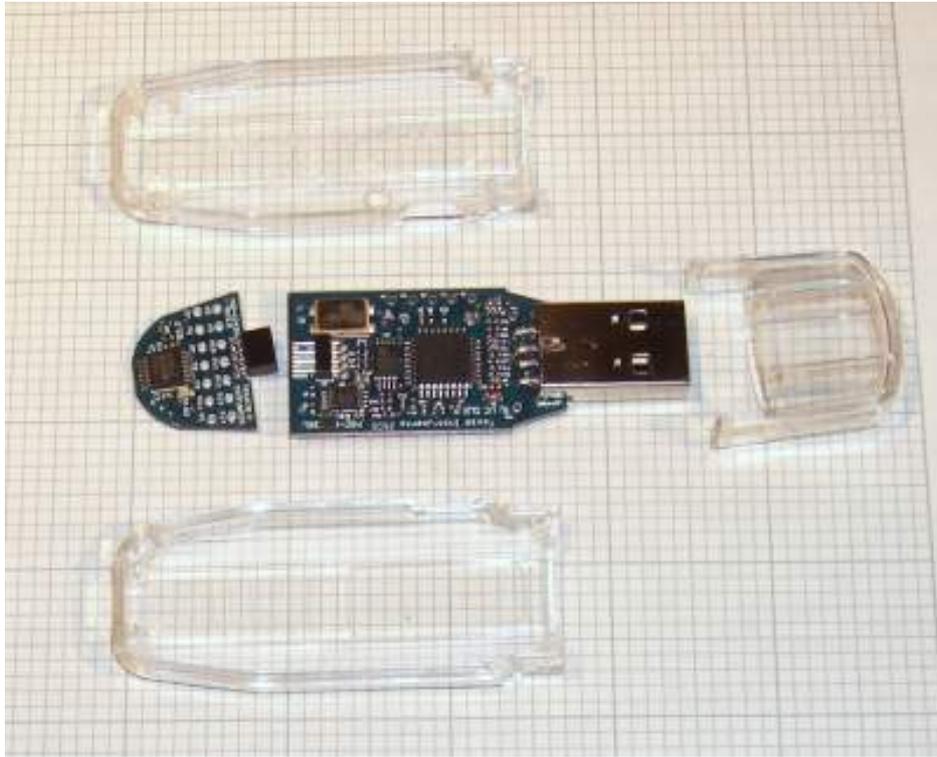
# PIC your micro

Sunday, 3rd June 2007 by Nophead

The official RepRap project uses Microchip PIC micro controllers. I have done several projects at work with these because they have such a wide range of parts that they often have the best fit price wise. However, I have never liked them very much. They have a horrible instruction set which does not lend itself to running C efficiently. Also, the development kit is a bit primitive by today's standards. When doing a home project ease of use and development kit cost becomes more important than part price. I have been following the RepRap forums and people are having lots of problems with a buggy open source PIC compiler and programmer.

I recently did a project at work which needed a micro with a very low power consumption so we used a Texas InstrumentsMSP430 series micro. I was very impressed with the USB key development kit which only costs \$20. For that you get an IAR C compiler, assembler, simulator and debugger. The instruction set of the chip is very small but has just the right instructions to run C efficiently and the C compiler does a good job of using them. The code size is limited to 4K but, as I am only using a 2K part, that doesn't matter. The USB key contains a programmer / "Spy Bi-Wire" in circuit debugger and a little detachable target board. The chip is surface mount but the target board brings all the pins out to a 0.1 inch header so you can incorporate it into a through-hole board and you can get additional target boards at \$10 for three.





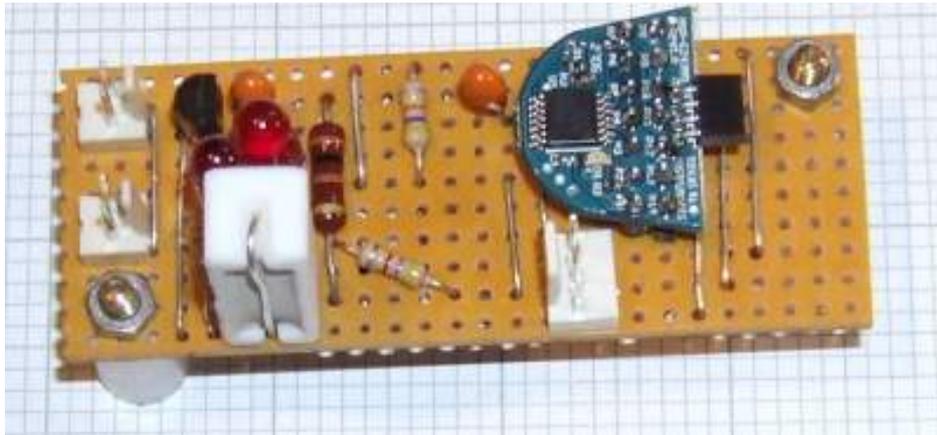
So for \$30 I get a development kit and micros to control four of HydraRaptor's heads.

The smaller parts don't have UARTs but they do have I<sup>2</sup>C which is easier to make a multi-drop bus with.

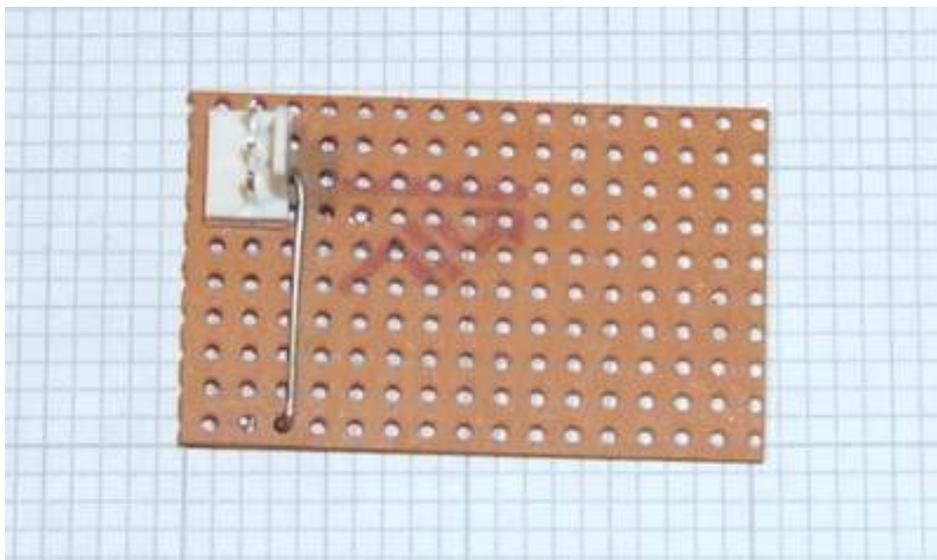
# Less speed more torque

Sunday, 3rd June 2007 by Nophead

This weekend I built a speed controller for my milling spindle motor, AKA Minicraft drill, after attending and recovering from the Stockport Beer & Cider Festival . I used one of the MSP430F2013 micros I described in the previous post. I built it on Veroboard, but hopefully all my future boards will be milled PCBs.



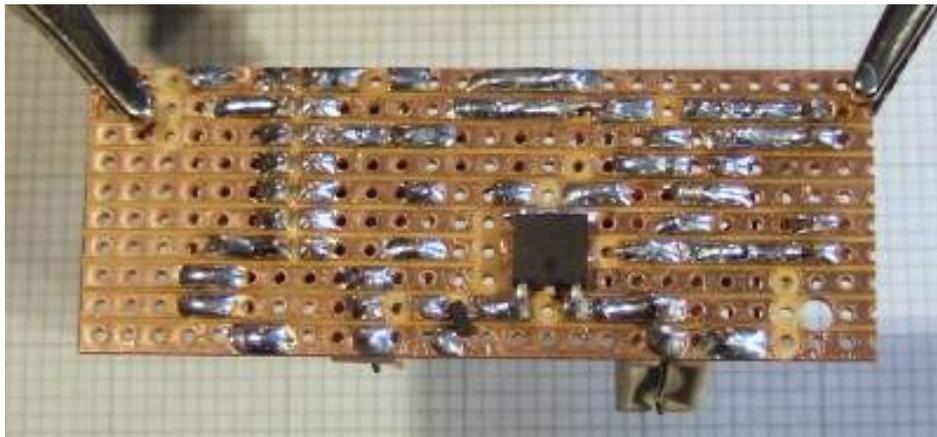
I never plan my Veroboard layouts in advance, I just make it up as I go along. In fact this circuit was so simple I didn't even draw a schematic. I did come a cropper this time though. I started on a board that was too small!



I only realised this after I had put on a regulator, LED and connector, so I had to desolder them and start again. The LED did not survive the ordeal. In my experience, they are one of the most fragile electronic components. They certainly don't like stress on their legs while being soldered.

The circuit is very simple, I will publish a schematic and the software when I complete it, assuming it works, which I have no reason to think it won't.

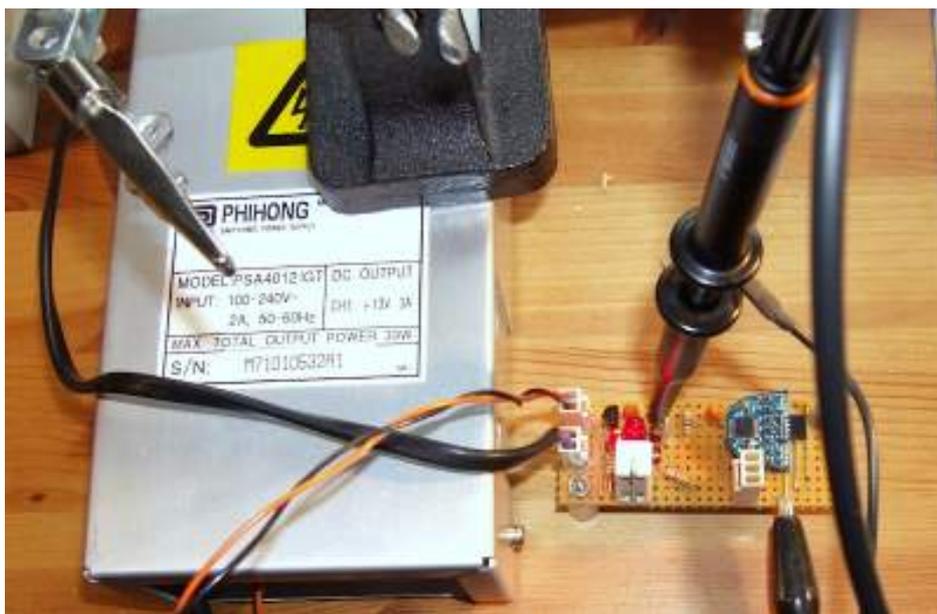
You may think "how is that puny little micro controlling a 40W motor"? What you can't see in the picture above are two surface mount FETs on the underside.



The big one is a BTS134D "smart low side power switch" with over voltage, over current, thermal and ESD protection. It has an on resistance of only 50m $\Omega$  so I can get away without a heatsink. With devices like these I don't know why anybody uses Darlingtons for switching nowadays. Darlington's have a fundamental flaw in that they cannot be saturated so the on voltage is over a volt leading to significant power dissipation, and hence a large heatsink, for these sorts of currents.

The tiny FET next to it simply boosts the gate drive from the 3V output of the micro up to 12V to ensure the big FET delivers the smallest possible on resistance.

The picture below shows the board being tested. It is connected to a 39W PSU, the drill motor and a scope.



I have verified that it can turn the motor on and off OK. It just needs some software now. The

micro has a timer with a PWM facility so controlling the speed of the motor should be pretty simple. The large resistor at the bottom left is for sensing the motor current. The micro has an ADC so I should be able to measure the speed to allow some feedback and also shut it off if it stalls. The unpopulated connector is the I<sup>2</sup>C link which will go to HydraRaptor's main controller.

# RTFM

Tuesday, 5th June 2007 by Nophead

I made a start on my PWM control software this evening. The first thing that I discovered was that I had connected the motor drive to the wrong pin on the MSP430F2013. There are two pins that can be driven from the timer, TA0 and TA1, but only TA1 is capable of PWM. I should have studied the datasheet more carefully! Easily fixed but a bit of a time waster.

I wrote a small test program to try different PWM duty cycles and frequencies :-

```
#include "msp430x20x3.h"

#define LED          BIT0
#define MOTOR        BIT2
#define FLOATING     (BIT1 + BIT3)
#define CURRENT      BIT4
#define GND          BIT5
#define I2CPINS      (BIT6 + BIT7)

#define OUTPUTS      (I2CPINS + MOTOR + LED + FLOATING)

int main( void )
{
    WDTCTL = WDTPW + WDTHOLD;          // Stop watchdog timer
    //
    // Set MCLK to 16 MHz, SMCLK = 2 MHz
    //
    BCCTL2 = SELM_0 | DIVM_0 | DIVS_3; // MCLK = DCO, SMCLK = DCO / 8
    BCCTL1 = CALBC1_16MHZ | XT2OFF;
    DCOCTL = CALDCO_16MHZ;
    //
    // Set up I/O
    //
    P1OUT = MOTOR;                    // Motor off
    P1DIR = OUTPUTS;                  // Define output pins
    P1SEL = MOTOR;                    // Motor = TA2 output
    //
    // Set up timer
    //
    TACCR0 = 20000;                   // 2 MHz / 100
    TACCR1 = 15000;                   // 25%
    TACCTL1 = OUTMOD_7;               // Reset / set
```

```

TAR = 0; // Start counting from zero
TACTL = TASSEL_2 + MC_1 + TACLR; // SMCLK, upmode, clear
}

```

I found that 50-100 Hz seems to work well. 1KHz is too fast as the current doesn't have chance the build up to its full value due to the motor winding inductance.

Here is a graph of motor current versus duty cycle with no mechanical load :-



As the duty cycle gets smaller the motor slows down so it generates less back e.m.f. making the current increase.

I chose a current sense resistor of 0.27 which gives voltages up to 1.75V however the full scale voltage of the ADC is only 0.6V so I could do with it being smaller. I could just attenuate it with a potential divider but as it gets hot and wastes power it is better to reduce its value to 0.1. Again, I should have paid more attention to the datasheet. I guess I will be taking a trip to Maplin tomorrow lunch time.

# Torque talk

Thursday, 7th June 2007 by Nophead

I updated my motor control circuit to use a 0.1  $\Omega$  current sense resistor to give me a full scale current of about 0.6A and then set up the ADC to provide negative feedback to control the speed. I read up on the classical control method which is PID, finding a good article on it here [www.embedded.com](http://www.embedded.com). Before embarking on that complexity I decided to try a simple more intuitive method. I wrote a program which turns the motor on and monitors the current until it falls to a specified level, indicating that the motor is generating the correct back e.m.f. i.e. running at the correct speed. It then turns the motor off and waits for the start of another cycle.

This algorithm works reasonably well after playing with a few numbers to get it relatively stable. It does however suffer from a beating problem. I am not sure exactly why but I think it must be the PWM pulse rate beating with the commutation of the motor. Here is a video of a scope trace of the current waveform. You can hear the motor in the background as the speed is swept from maximum to minimum and you can see the current pulses getting shorter and higher. Just to confuse matters the scope trace is beating with the camera frame rate.

I don't think the beating will matter much but it is a bit annoying. Playing with the PWM frequency has a big effect on it. In the end I settled for 200Hz, but I may play about with it a bit more.

One thing that I hadn't realised, but is obvious really, is that when you slow down a motor with PWM it loses a lot of torque at low speeds but when you add feedback it gets it all back again.

Here is the simple piece of code :-

```
#include "msp430x20x3.h"

#define LED          BIT0
#define MOTOR       BIT2
#define FLOATING    (BIT1 + BIT3)
#define CURRENT     BIT4
#define GND         BIT5
#define I2CPINS     (BIT6 + BIT7)

#define OUTPUTS     (I2CPINS + MOTOR + LED + FLOATING)

typedef unsigned int word;
typedef char bool;
#define true 1
```

```

#define false 0

int main( void )
{
    WDCTL = WDTW + WDTW; // Stop watchdog timer
    //
    // Set MCLK to 16 MHz, SMCLK = 2 MHz
    //
    BCSCTL2 = SELM_0 | DIVM_0 | DIVS_3; // MCLK = DCO, SMCLK = DCO / 8
    BCSCTL1 = CALBC1_16MHZ | XT2OFF;
    DCOCTL = CALDCO_16MHZ;
    //
    // Set up I/O
    //
    P1OUT = MOTOR; // Motor off
    P1DIR = OUTPUTS; // Define output pins
    SD16AE = CURRENT + GND; // Configure analogue inputs
    //
    // Set up ADC
    //
    SD16CTL = SD16XDIV_2 + SD16DIV_0 + SD16REFON; // MCLK / 16 = 1MHz
    SD16CCTL0 = SD16DF + SD16OSR_32 + SD16IE + SD16SC; // OSR = 32
    SD16INCTL0 = SD16INTDLY_0 + SD16INCH_2; // Delay 4 clocks; channel A2
    //
    // Enable interrupts and wait forever
    //
    _BIS_SR(GIE);
    for(;;);
}

int current;
int target_current = 5000;
#define CYCLE 200

#pragma vector=SD16_VECTOR
__interrupt void ADC_int(void)
{
    static int count;

    int adc = SD16MEM0;
    current += (adc - current) >> 1; // Moving average filter
}

```

```

if(++count >= CYCLE) {
    count = 0;

    P1OUT &= ~MOTOR;           // Motor on

    P1OUT |= LED;

    if(target_current < 0)
        target_current = 5000;

    target_current += 10;
}

if(count > 30 && current < target_current) {
    P1OUT |= MOTOR;           // Turn the motor off

    P1OUT &= ~LED;
}
}

```

Note that in the end I am not using the PWM capability of the MSP430 timer as I did the motor control in the ADC interrupt handler.

The next task is to get it talking to the rest of HydraRaptor using an I<sup>2</sup>C bus.

# Lenz's law

Saturday, 9th June 2007 by Nophead

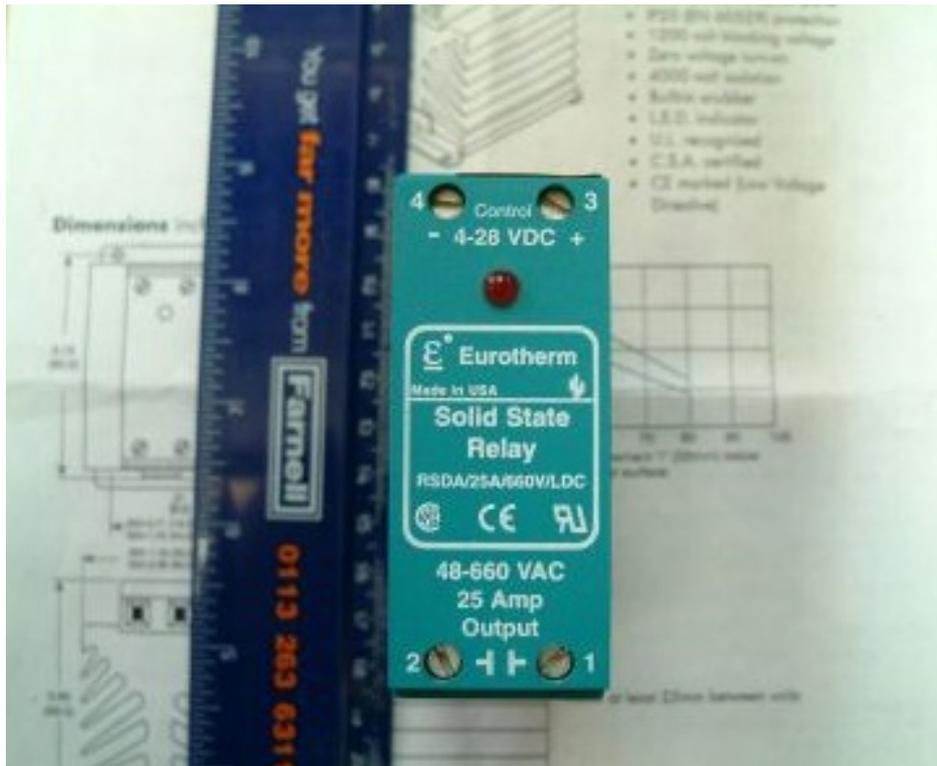
Explain this: I just connected my 1300W vacuum cleaner to a power meter. When running unobstructed it consumes 1100W. When I block the tube so the motor is audibly under more load the power drops to 900W. Power factor remains close to 1. Weird motor?

# Rewire

Monday, 11th June 2007 by Nophead

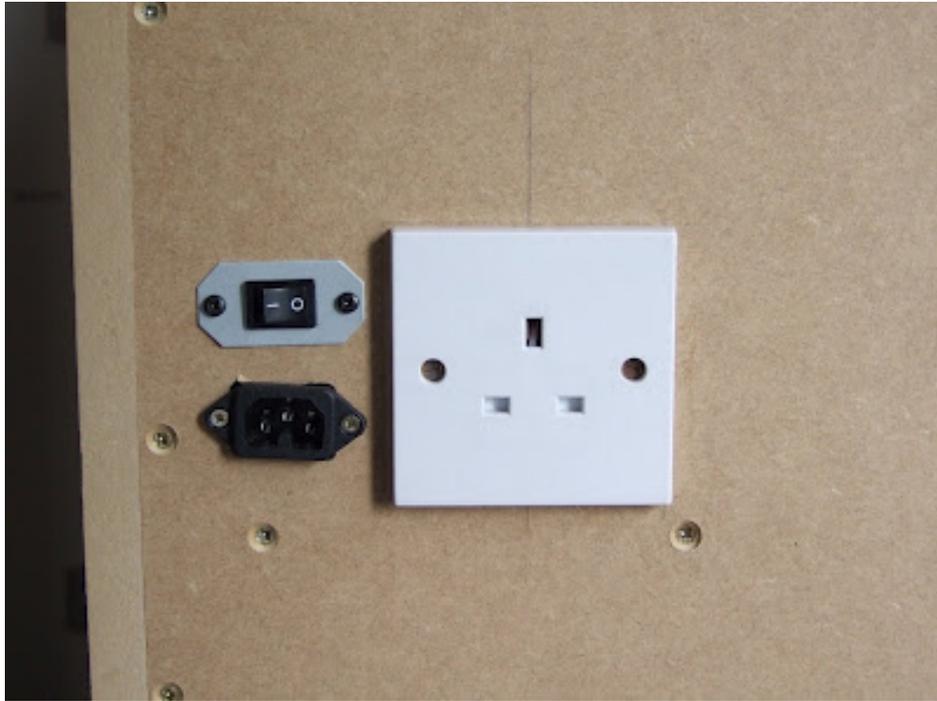
Well I got dissed at work today for my two line post over the weekend so I thought I had better post something more substantial even though I don't have much news. I spent most of the weekend rewiring HydraRaptor when I wasn't watching the Formula One Grand Prix.

I got a solid state relay from eBay for £16 to control the vacuum cleaner. I have had reliability problems with SSRs in the past so I went for something with plenty of headroom.

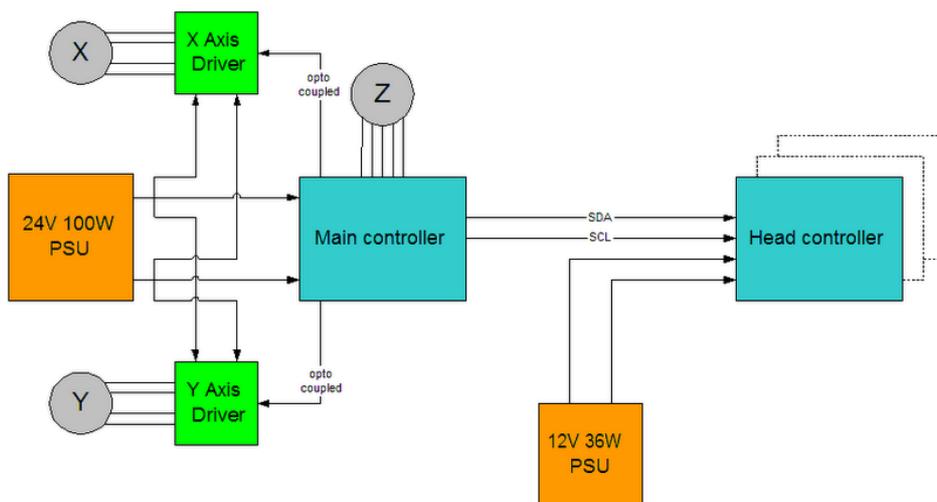


It's rated at 660V 25A with 250A 1200V surge capability. It's completely over the top and I know I could have got something a lot cheaper but it looks impressive.

The vacuum cleaner is rated at 1300W so it can theoretically draw 5.4A although it measures a bit less. This plus the rest of HydraRaptor exceeded the rating of my mains inlet which was 5A. If it was a plain socket I might have chanced it with a small overload but it was a cheap filtered inlet from an old PC PSU so I didn't want to risk it. I had to upgrade to a 10A inlet socket and upgrade the mains lead. I installed a 3 pin outlet socket on the back of the machine for the vacuum and I then had to fuse back down to 3A for the rest of the internal wiring.



I also installed the spindle motor speed controller and a 12V 3A power supply. While it may seem wasteful to have two separate power supplies it does have one big advantage. The main controller and the stepper motors are powered from a 24V 100W PSU. All the heads will be powered from the 12V supply and linked to the main controller with an I<sup>2</sup>C bus. Both PSUs have floating 0V rails so there will be no motor current flowing down the comms ground between the two controllers. This will allow me to use only single ended 3.3V signals rather than differential or RS232 signals which would normally be needed to combat ground bounce. Here is a block diagram. As you can see there are no signal grounds shared with power grounds and there are only four wires from the main machine to the heads. Once I am able to make PCBs I will shrink the motor controller using surface mount components and mount it on the Z axis together with a similarly shrunk extruder controller.



Here is the current state of the machine, getting ever more complicated :-



Just software now to complete the milling machine and then on to extruder.

# Disaster, frustration, success, disaster

Monday, 18th June 2007 by Nophead

Not posted for a while because I couldn't get the I<sup>2</sup>C link between my main controller and the spindle controller working. Before that I had a minor disaster when I crashed the drill chuck into a block of plastic. It appears to have bent the shaft out of true as the tool runs a little eccentrically now. The drill was made by Minicraft but they seem to have gone out of business. This made me realise how precarious it is to make something out of surplus components and things you have to hand rather than readily available parts. If I break anything then it might be impossible to get a drop-in replacement. Something like the \$4000 XY table I got for \$400 would be virtually irreplaceable.

Fortunately the drills seem to crop up on eBay fairly often. I got one almost identical except that it has a collet chuck rather than a three jaw one. It seems to have a bit of end play but this appears to be due to the bearing being loose in the housing rather than having play itself. I should be able to fix it with glue or shim it with a washer.

The I<sup>2</sup>C problem was a nightmare. I could get it to work if I stepped through the code at either end but not if I ran it. I was fairly sure the software was right because I had used the MSP430F2013 code before on a very similar device and it was based on an app note. The code at the MC9S12NE64 end was a translation of some code I used recently on a Coldfire which seems to have an almost identical I<sup>2</sup>C module. Not surprising as they are both Freescale devices.

Obviously it was a timing issue but all the timing should be done by the hardware. I am only running it at 100K baud and with 1K pullup resistors over 4 inches of cable I should have no problems. Looking round the Web I found an errata for the MSP430 which seemed to have lots of I<sup>2</sup>C bugs in the B revision of the chip with no workarounds. Mosts of these are fixed by revision C but my chip seems to have an X where the die revision should be.

Because the problem manifested itself as a lockup it wasn't possible to get a repetitive signal to look at on my analogue scope. I decided I should really have a digital storage scope for these types of problem so I ordered a cheap USB scope front end made in China from a company in the US. \$360 plus shipping for 100MHz bandwidth, two channels, 250 MSps. Not bad if it works and the software is half decent. Most software to support hardware seems to be complete rubbish these days. I have had four PC TV cards so far each with decent hardware but software that is utter crap.

While waiting for it to arrive I decided in desperation to try reducing the clock speed of the MSP 430. To my amazement dropping it from 16MHz to 8 MHz appeared to fix the problem. So definitely hardware not software then.

Flushed with success I added a Python function to control the drill speed by sending a command via Ethernet to the main controller which forwards it by I<sup>2</sup>C to the head controller. This worked fine but as soon as the drill made contact with the tool height sensor for the first time the sensor stopped working. I thought the shaft of the drill was ground but actually it was +12V. Now that the power supplies are linked by the comms cable it stuffed 12V into two of the 3.3V inputs of the MC9S12NE64 and not surprisingly they don't work anymore! In fact I am surprised any of it still works but most of it does.

So, major disaster. It will be very difficult to replace the chip as it is fine pitch surface mount. I do have some spare inputs I could use providing the rest of the chip holds out. I can probably still buy another demo board but its starting to get expensive repairing my mistakes.

Curiously the replacement drill seems to have an isolated shaft. I knew the first one wasn't but I assumed it was ground not +12V. However, it wouldn't have made any difference because foolishly I switched it with a low side driver so when it is off both wires are at 12V!

So now I have to rewire the tool sensor inputs, add some protection and cobble the two drills together to make one good one, preferably using the motor with the isolated shaft. The I<sup>2</sup>C comms need beefing up a bit with a CRC, packet sequence flag and an acknowledgment / retry mechanism. I also want to add drill stall detection and employ the shaft encoders on the XY table to detect that stalling as well. Hopefully then I will avoid any more costly tool crashes and move on to making the RepRapextruder.

# The day the music died

Thursday, 21st June 2007 by Nophead

Although I am fortunate enough to have a project room which is nearly 3m by 4m, as you can see it almost completely full of junk.

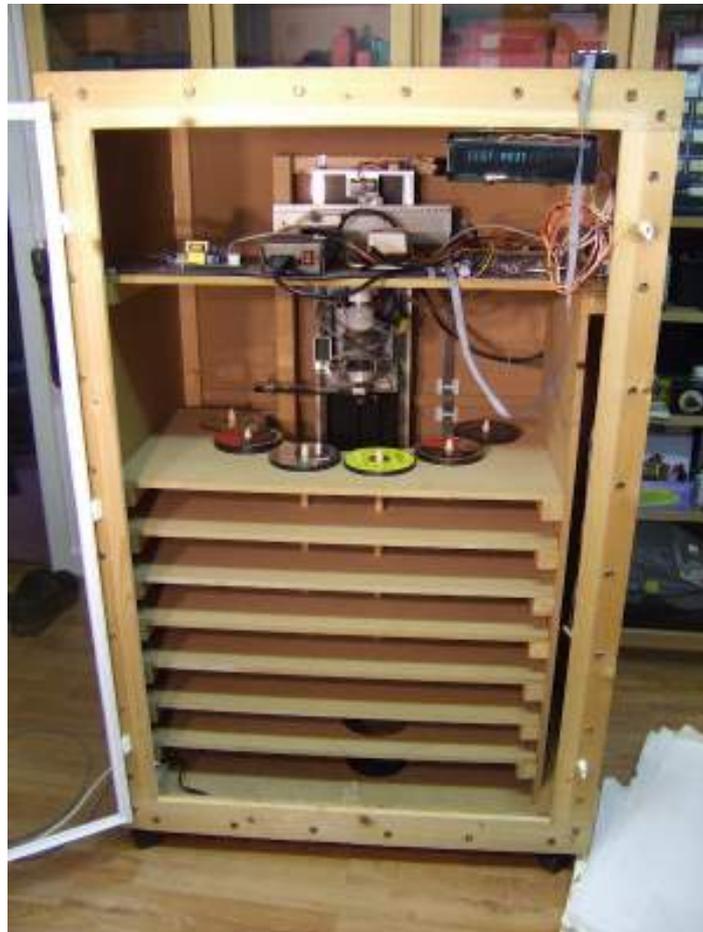


The large glass fronted MDF box on the far left next to HydraRaptor is a 400 CD jukebox that I designed and made in 1990. I used it for about 10 years until the CD player's laser wore out. At that point I ripped all the discs and stored them on my PC as mp3s. I haven't used it since but I could never bring myself to dismantle it as it is probably the best thing I have ever made. However, this week I got fed up of not having enough work space so I decided it had to go.

This is what it looked like. It had a sealed glass door on the front which is hard to photograph.



Here it is with the door open.



The discs were stacked 10 high on wooden pegs arranged in semi circles of six on seven shelves, i.e. 42 sites. The bottom shelf had a hole in it above the open CD player drawer and an empty peg used to store the next disc to be played.



That left 40 pegs of ten discs giving a maximum capacity of 400 discs. Worst case, to play a disc at the bottom of a peg, involved moving the nine discs above it to three nearest neighbours. This took about 40 seconds but as long as the playlist was not empty it would get the next disc ready

and place it on the peg next to the player. It would then move the discs it had moved out of the way back onto their home pegs. Then it would hover above the player waiting for the disc being played to finish. When it did it would lift it out of the drawer and stash it on an the adjacent peg. It would then insert the new disc and while that was playing it would return the previous disc to the top of its home peg. That way the most popular discs tended to be at the top of their pegs for fast access.

The discs were moved by a robotic arm with a rubber suction cup on the end made out of a toy dart.



This was moved radially by a stepper motor with a gear box. It was attached to a trolley on steel rails which was moved vertically by a toothed timing belt driven by a large 12V DC motor with a gear box. As you can see the end of the arm has three micro switches. The left hand one was used during initialisation to find the home position of the arm. The other two were just for safety. The vertical motor is so powerful it could easily snap the arm off so I wired the limit switches in series with the motor so if the software crashed and left the motor running it would do no damage.

The arm is actually made of two pieces of perspex clamped together at the hub. When the arm descends onto a disc the top piece bends way from the bottom piece and a pair of switch contacts between them part. Again this was in series with motor for safety.

Here is a view of the electronics shelf after I removed the top :-



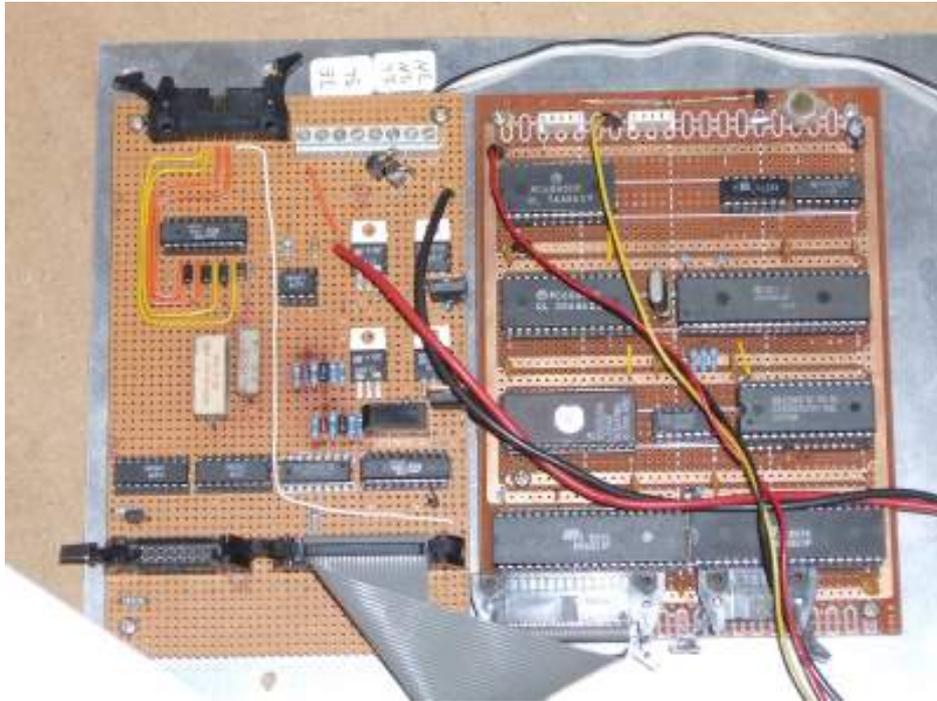
On the far left is a mains modem which allowed my PC upstairs to communicate with it when it was in its original home in an under stairs cupboard.



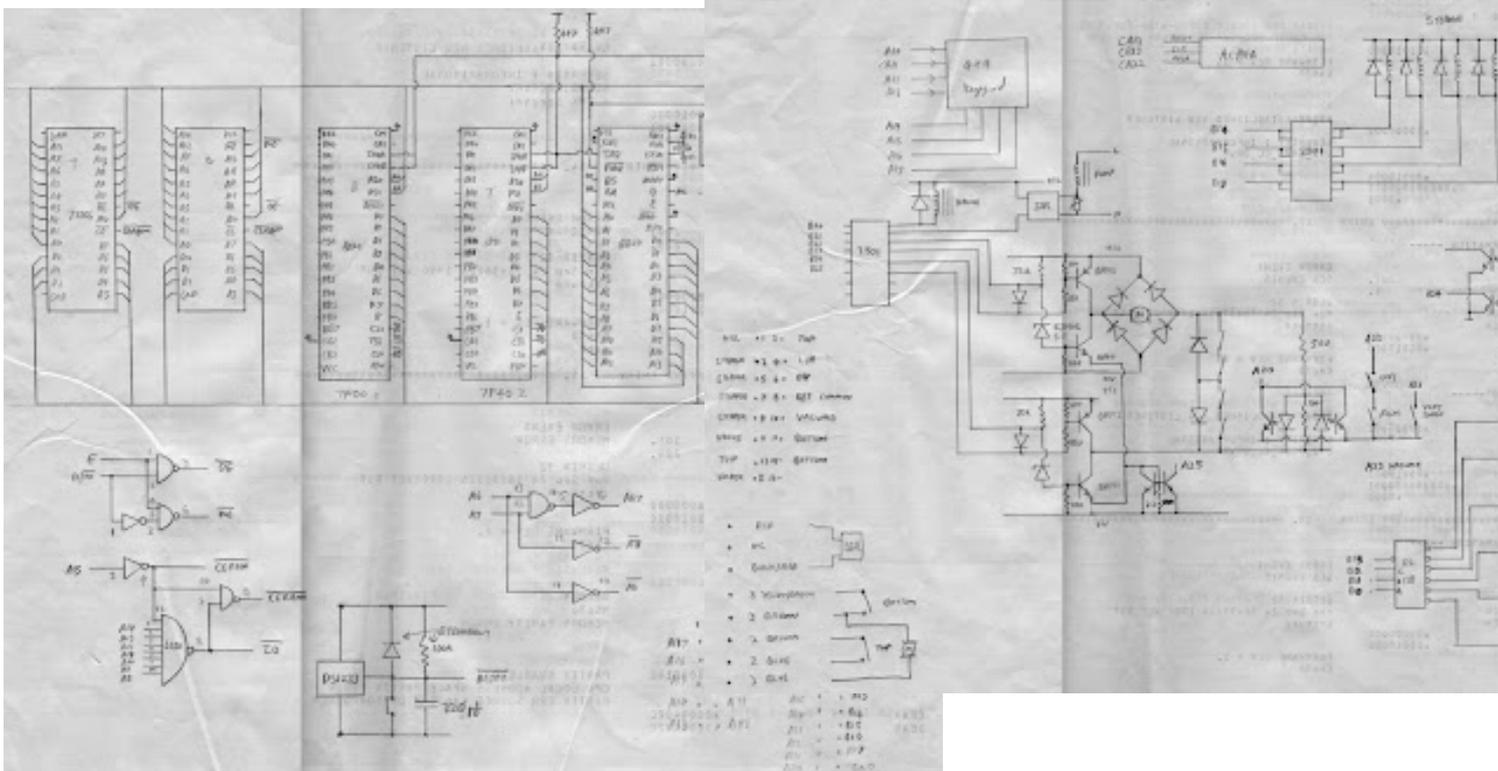
Next to that is a small switch mode PSU which powered everything.

In the middle is an aquarium pump which I used to generate the vacuum to lift the discs. I converted it from blowing to sucking by sealing the case and connecting a pipe to the air inlet underneath.

On the right is the controller :-



This is a Motorola MC6809 microprocessor with 32K battery backed RAM, 32K EPROM, a timer, a UART and two PIAs. Nowadays this would be a single chip. Here are the circuits, no free ECAD programs in those days :-



Here is a view with the electronics removed :-

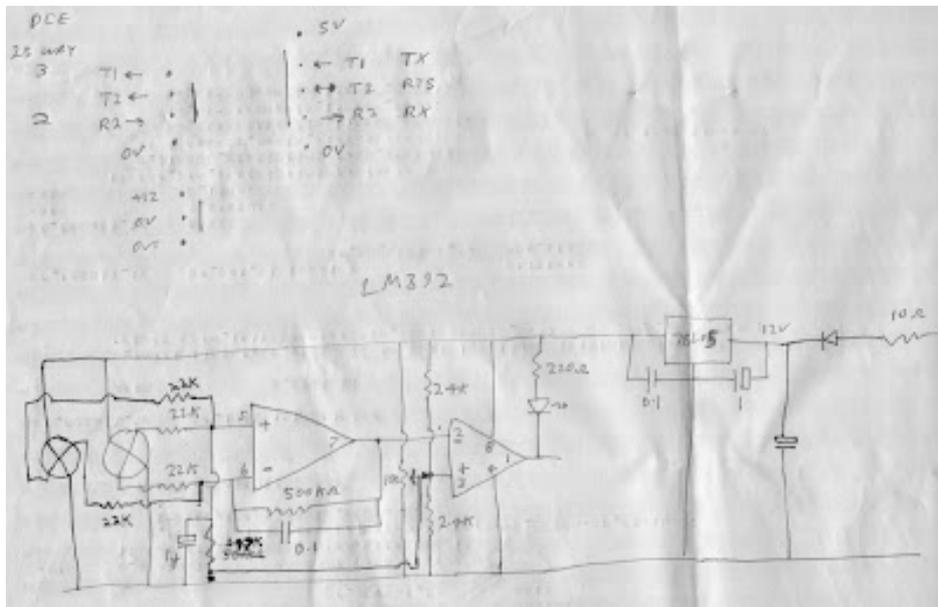


Here is a close up of the mechanics :-



The vacuum pump took a while to build up pressure and release it again so I made a solenoid operated 3 way valve to turn the suction on and off quickly.

The top circuit board is an opto detector which looked at tabs on the right hand rail to know where the shelves were. The board below it is a vacuum pressure sensor to enable it to know if it had failed to pick up or dropped a disc. That only happened during development really but it was vital to detect it otherwise it would lose track of which discs were on which pegs. Originally there was just one vacuum sensor but about twice a year I had to recalibrate it. Eventually I realised this was because the change in atmospheric pressure, due to weather, was greater than the vacuum level. I fixed it by adding a second sensor and measuring the difference between the vacuum pipe and atmospheric pressure. Not a very cost effective solution as the sensors were about £13 each.



Here is a video of it moving some discs. I had to drive it manually from the test routine as it would not run without a working CD player.

You probably will have noticed that each time it picks up a disc it pauses over the peg for a while. This was because the discs tended to stick together by suction after being pressed by the weight of the ones above. This was mainly cured by putting a small circular spot label near the centre of the disc to break the seal. The delay gave time for the second disc to drop back onto the peg if it did initially lift.

So now it is no more, but perhaps I might reuse the vacuum system and the metre long axis for some sort of pick and place machine.

# Bodge it and move on

Monday, 25th June 2007 by Nophead

The I<sup>2</sup>C nightmare continues. I thought slowing the clock of the MSP430 had fixed the problem. However, it still locks up after a few packets. The symptoms are that the MC9S12NE64 decides that the MSP430 has not ACKed the address byte. At this point both clock and data are low. The MC9S12NE64 sends a stop and both lines go high. It then thinks the bus is permanently busy. If I reset the MC9S12NE64 then it works for a while again so the MSP430 is not locked up.

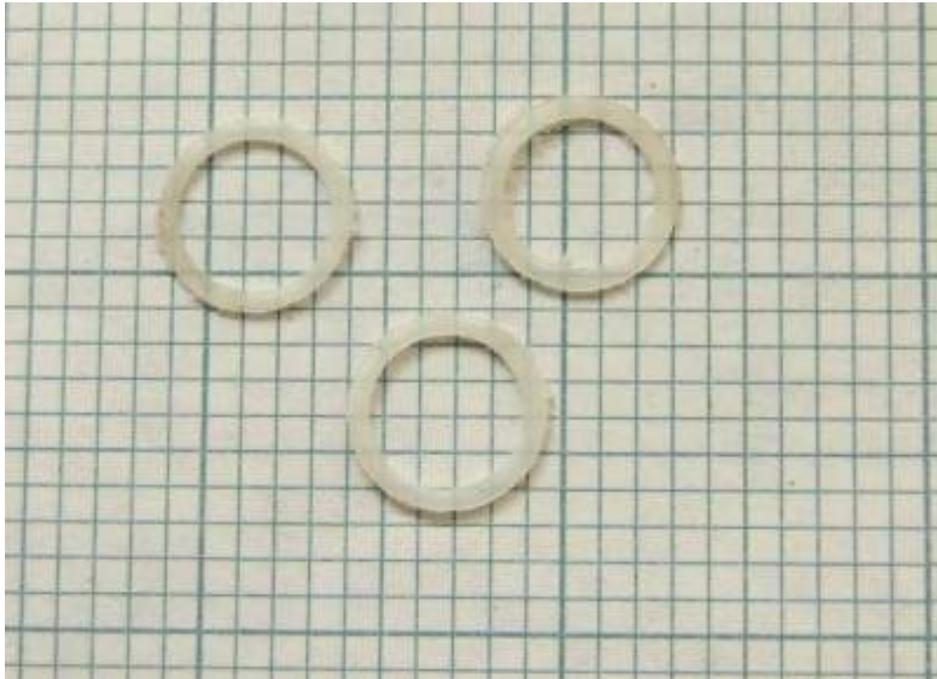
So my first bodge was to detect the MC9S12NE64 thinking the bus is busy when it should not be and reset its I<sup>2</sup>C module. This caused it to lock up thinking the bus was not busy when it should have been. In desperation I added a 100us delay after the reset and now it works.

It looks like my digital scope will not arrive for at least a couple of weeks so I can't really get to the bottom of this until then but at least it is working with retries. I haven't done a lot of I<sup>2</sup>C stuff in my career but it looks like a really clever protocol. Less wires than SPI but has defined start and stop codes, multi-master arbitration and auto clocking down to the slowest device. As both ends implement it in hardware I just expected it to work. I should have known better as most hardware has bugs these days like all software.

# End of play

Tuesday, 26th June 2007 by Nophead

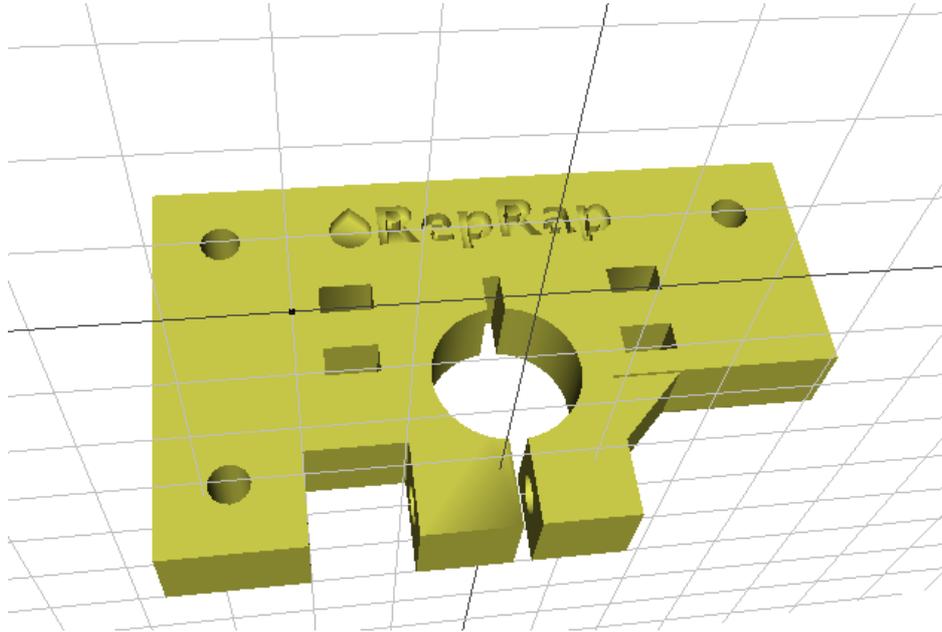
You may recall that I said my replacement spindle motor, AKA Minicraft drill, had a bit of end play due to the bearing moving. This evening I made some shim washers by milling a thin piece of hard plastic that I got from the inside of a PC power supply. They are 11mm diameter with a 8.5mm hole and about 0.2mm thick. They were a bit ragged round the edges due to the plastic burring quite badly but it didn't really matter. I made three but two were enough to stop the bearing moving.



This is what the inside of the drill looks like. I added the capacitor myself to keep the radiated emissions from the cable to a minimum.



The result was very pleasing and I now have a working milling machine again. My next job will be to mill an FDM extruder. I plan to start with the clamp as this looks the easiest part.



Obviously I will have to modify it a bit. For example I can't do sharp internal right angles due to the tool's radius.

# Bob on

Friday, 29th June 2007 by Nophead

Here is the first RepRap part that HydraRaptor has milled :-



It is the extruder barrel clamp as shown in the previous post. As you can see it is dimensionally correct to two decimal places! It's not a fluke, the height is bob on 45.00mm as well. I have been getting pretty good accuracy with my previous milling attempts but this is astonishing.

I used a smaller end mill (2.22mm) in a collet chuck which is more accurate than the three jaw chuck I used before. The plastic is a sheet of 9mm Delrin or Acetal which I used because I read somewhere that it was a good plastic for machining. It did machine well but all the edges were left with a thin burr. This was fairly easy to remove with a fingernail.

This is not the latest version of the RepRap design but I decided it would fit my machine better. I added two more mounting holes and changed the central hole diameter to match my PTFE barrel which is 12mm rather than 10 or 16mm in the original design. The central slot is 2.5mm rather than 2mm because my bit was too big. Obviously I will have to drill the horizontal hole for the clamping bolt with a drill press.

Here is an edited video of it being made, it took around 20 minutes to make the part :-

And here is an amusing out-take if you listen to the sound :-

So having achieved perfection on this first part, things can only get worse when I attempt to make the rest of the extruder.

# Coupling

Sunday, 1st July 2007 by Nophead

Well in my last post I said things could only get worse and they did! I picked the extruder motor coupler to make next as it looked easy. Ironically the first thing I did was to destroy my z-axis motor coupler by getting the vacuum pipe trapped underneath the drill. It's amazing how much torque a decent stepper motor can deliver. Fortunately I had another stronger coupling lying around.



The only problem was that the hole for the shaft was only 6mm and my shafts were 1/4 inch. Luckily I possess one reamer and it happens to be 1/4 inch. I didn't even know it was a reamer until a friend told me it was recently. I thought up to then it was a milling bit. It got a bit toasted the other day when I used it to cut MDF at 30000 RPM. Still it worked on aluminium like a dream with some paraffin lubricant and my drill set to its slowest speed.



The machine is a lot noisier with the thicker coupling so perhaps a rubber one would be better.

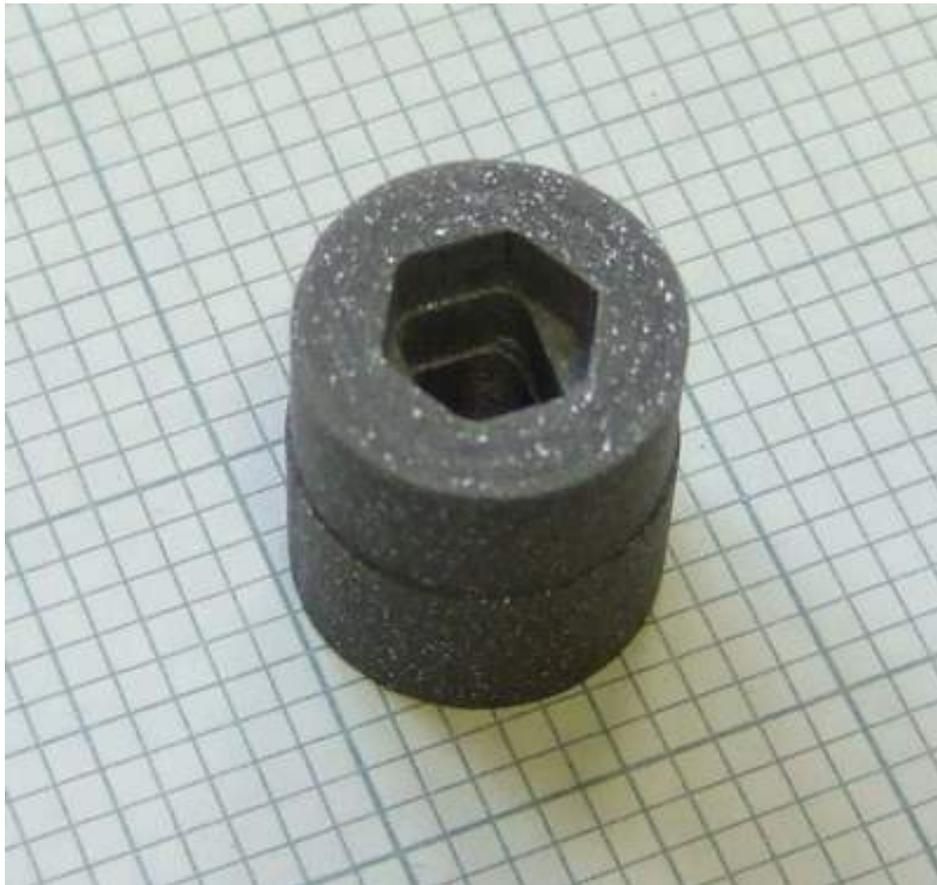
The next disaster was that I dropped my camera on the floor and broke the USB connector so I had no way to get the pictures off it. Surface mount connectors are a nightmare. They make production cheaper but they are just too fragile for external connections. It broke off the PCB and all the pins came out. I managed to solder it back on and press the pins back in, hence these photos.

Milling the coupler was tricky because the small milling bit I used to keep the corner radii small has limited reach because its shaft is 0.3mm bigger than its head.



The coupler is 16mm deep so I had to step the outside out 0.2mm half way down. Similarly the inside slot had to step in. It made the programming complicated because in order to step out part way down you need to have opened up the gap to the scrap above. I.e. you have to cut a sort of stepped V shaped trench needing three passes.

The final result came out OK



It couples the motor which has a round shaft with two flats to a hexagonal nut. Here it is attached to the motor :-



I have made a start on the polymer pump halves but they have curved upper surfaces requiring a ball end mill and true 3D milling so a bit more programming is required.

# All hands to the pump

Tuesday, 3rd July 2007 by Nophead

I finished milling the polymer pump casing this evening. Here it is :-



The bearing gaps gave me some problems because they require a small ball end mill with a relatively long reach. As I said before all my small milling bits have shafts bigger than their heads.



Rather than order one from the US and wait for it to come I decided to try grinding down the shaft of one of the ones I already had. I put it in the lathe but it was too hard to be turned down with a cutter. Instead I put a small grinder in my Minicraft drill and held it against it while it was spun in the lathe. This worked quite well as you can see :-



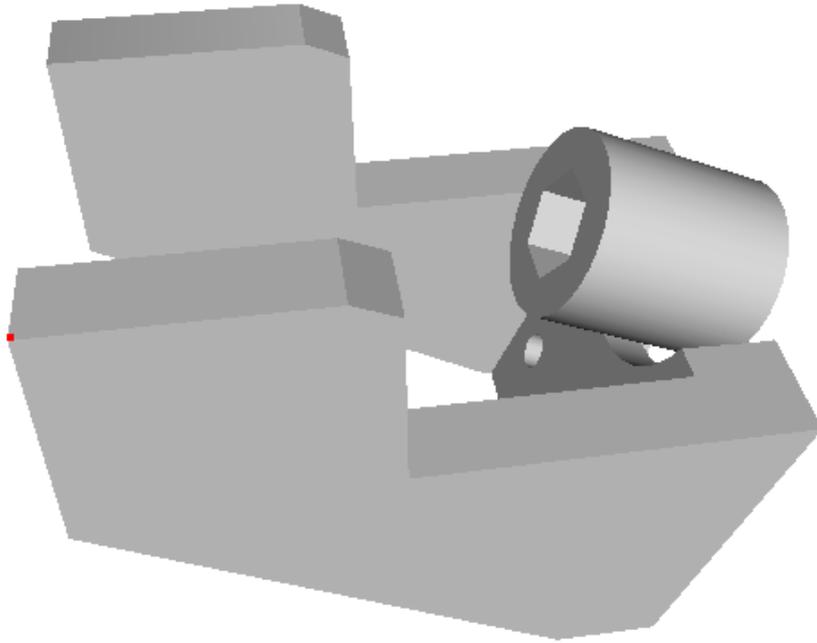
The parts aren't exactly to the ArtOfIllusion models provided by RepRap. Obviously internal corners have a minimum radius due to the tool being a finite size so I will have to bevel the outside edges of the bearings a little. Both the polymer channel and the bearing gaps have a slight overhang in the models. While this would theoretically be possible with a larger ball mill it would make the programming more complicated. Hopefully I can get away without it.

I also increased the bore of the polymer channel from 3 mm to 3.2 mm as my reel of HDPE is a bit over sized. I am still a bit worried about this being too tight. Also the material I used is not as slippery as say PolyMorph so there may be too much friction. I think I will open it up slightly with some fine emery paper and then polish it with wax.

# Peck it till it squeaks

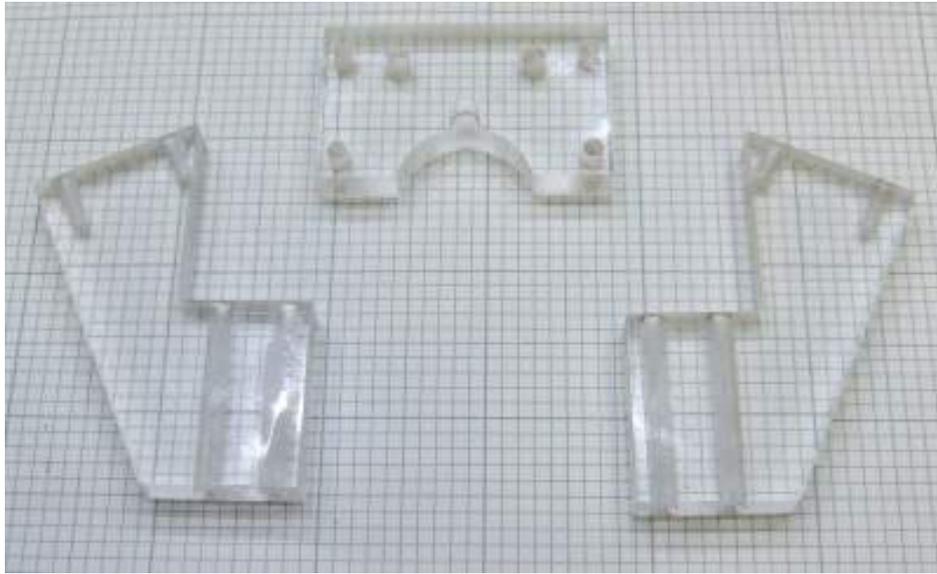
Tuesday, 10th July 2007 by Nophead

Not much progress recently as I spent the weekend at the British F1 Grand Prix. The next part of the extruder that I made is the motor holder. Surprisingly this gave me the most trouble.



Obviously, as it is a 3D structure with overhangs, it cannot be milled out of a solid block and would be very wasteful of material if it could. Instead I made it out of three pieces of 6mm Perspex sheet. I always think of this as being pretty flat but in fact its thickness varied by about 0.25mm across a six inch square cut from a larger sheet. This wasn't a problem however.

The first problem I had was getting the dimensions from ArtOfIllusion. For the other bits I have been clicking on sub components of the object to get the size and position. In this case the model seems to have been constructed in a different way so I could not select sub parts. Also there seems to be no rulers or dimensions in AOI and the grid labels are poor. In the end I redesigned it in Visio taking measurements from the motor itself. The shape of mine is a bit simpler but I think it holds the motor in the right place so it should work.



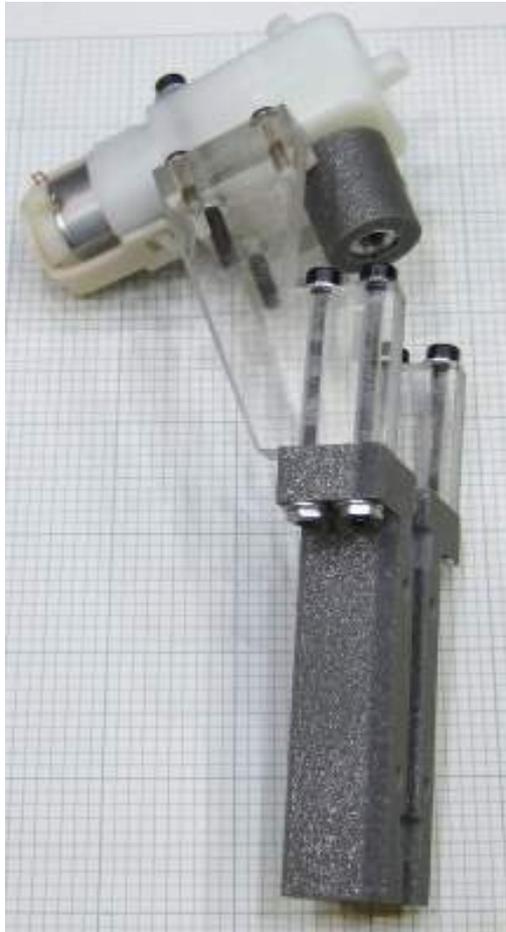
Milling these three parts was straightforward, the hard part was drilling the holes along the plane of the sheet. There are four M3 clearance holes which are 24mm deep. These are very hard to drill in Perspex without getting the drill stuck and very time consuming. The way I did it was to make a paper template with cross hairs in Visio. I cut it out and aligned it with the edge to be drilled. I then marked the centre by drilling a few mm with a 0.5mm drill in a hand held pin vice. I then drilled the holes using a very slow drill in a drill press and the piece in an improvised drill vice. I started with a 2mm drill then opened them out with 2.5mm and 3mm drills.

You can only drill a few mm at a time before the drill starts to bind because the swarf clogs the bit and then the Perspex melts and sets again incarcerating it. You can't then turn the drill backwards or forwards. The first time this happened I thought I was going to have to smash the workpiece to recover the drill and start again. However, I did find a less drastic way to get the drill out. I put it in a spare chuck which is the good old fashioned type with a chuck key. I tightened this as much as I could, rested the workpiece on top of vice jaws with the chuck below and tapped it with a hammer. This does work, I had to do it several times.

You have to use a pecking action while drilling. I drill until I hear the Perspex squeak which indicates the onset of binding. I then back out and brush off the swarf and repeat. Very tedious, perhaps a lubricant would help but I have no idea what to use on Perspex.

To fasten the pieces together I chose M2.5 screws and decided to tap the Perspex. The only problem there is that I have a set of large taps that go down to M3 and a set of small taps that go up to M2. I thought tapping M3 in 6mm Perspex was likely to crack it so I decided to try using the screws to cut their own thread. That was a nightmare with binding and the heads shearing.

Anyway, eventually I got it done and am quite pleased with the result.



At some point I will mount a drill vice on my X-Y table, add a laser centre finder and create a highly accurate semi-automatic drill press. Hopefully I can monitor the motor current to detect the onset of binding and make the pecking automatic.

Now I need to do some lathe work to make the moving parts, barrel and nozzle.

# Dinner and Delrin

Tuesday, 17th July 2007 by Nophead

I am used to being inundated with HDPE milk bottles but it's something when your dinner guests bring you a bottle of wine and a carrier bag of Delrin scraps! Very welcome of course.

Not posted for a while because, apart from entertaining, I have been puzzling over how you drill a centred hole in the end of a long workpiece using a lathe. Several of the RepRap extruder parts need axial holes drilling down the middle of them. On a normal lathe these parts would not be considered long. They would be pushed back inside the chuck, so that the end which meets the drill mounted in the tail stock is well centred. On the scale of watch parts they are massive so they are too big to fit down the spindle of my watchmaker's lathe. If I put the far end in the chuck then the near end drifts out of centre. Normally you would support a long item with the tail stock when turning it, but how do you support it when drilling?

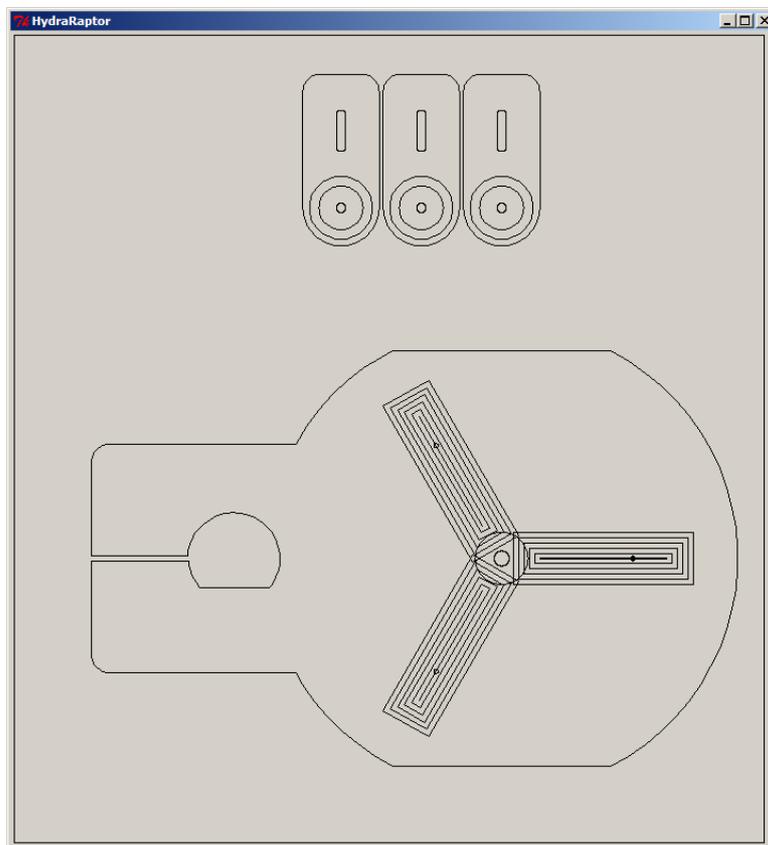
Here is a picture of a 1mm pilot hole being drilled in M5 threaded rod with a drill guide. Although this was only slightly off centre each successively bigger drill wandered further out.



The problem is not unique to my small lathe as it would occur with larger parts on a larger lathe. I searched around the web for a solution but I did not find one, so I decided to solve the problem by making a new part for the lathe. Not sure what to call it but it is a sort of inside out live tailstock. I.e. rather than having a bearing which meets the end of the workpiece, it has three rollers which support the outside of the workpiece, keeping it centred but allowing it to turn freely with access to its end for drilling.



This is the largest thing I have milled so far, so not wanting to risk wasting time and material, I decided to add a tool path simulation view to my Python script. As I have come to expect with Python this was trivial. A quick Google found me the Tkinter package. A quick scan through the tutorial and ten lines of code later here it is:-



I don't know if the new device works yet but it looks promising. Here it is with some M5 threaded rod spinning in it:-



I don't know if I have invented a new tool or just reinvented the wheel, or three wheels to be precise.

# Steady on

Wednesday, 18th July 2007 by Nophead

A friend pointed out to me that actually I have reinvented the "three point steady". Here are some examples I found on the web :-





Incidentally the only reason mine has flat sides is because the width was limited by the size of the raw material .

I have not had a chance to try it out yet, but it looks like I am on a well trodden track.

I have had a request to show the ten lines of Python which draw the simulation window. These are

:-

In the constructor:

```
self.root = Tk()
self.root.title("HydraRaptor")
frame = Frame(self.root)
frame.pack()
self.canvas = Canvas(frame, width = 710, height = 765)
self.canvas.create_rectangle(-70*5, -76*5, 70*5, 76*5)
self.canvas.pack()
```

In the destructor:

```
self.canvas.config(scrollregion=self.canvas.bbox(ALL))
self.root.mainloop()
```

In the feed\_xy function:

```
self.canvas.create_line(self.xy[0]*5, -self.xy[1]*5, pos[0]*5, -pos[1]*5)
```

I am sure there is a better way to do the scaling, replacing the magic numbers with constants would be a start!

# Bearing up

Sunday, 22nd July 2007 by Nophead

The bearings for the extruder pump are supposed to be made from brass and I had a bit of brass rod earmarked for the job. It is only 9mm diameter but the bearings are supposed to be 10mm. I had planned to make the holes in the pump housing smaller to compensate but I forgot. While wondering what to do I just happened to find a 10mm steel pin lying around at a rubbish tip.



The fact that there is no rust on it suggests that it is some form of stainless steel. It is certainly quite hard. I tried to cut it on the lathe with a parting off tool and all it did was take the tip off the tool.

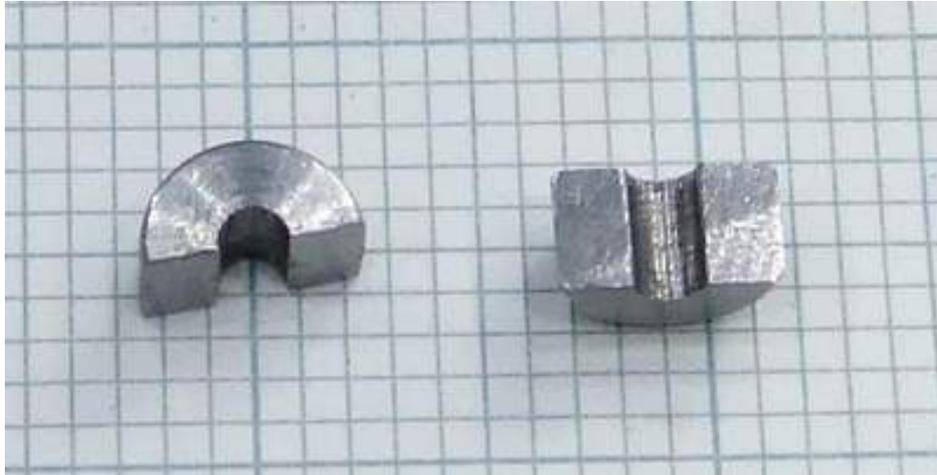


I next tried cutting it by holding a hacksaw against it while spinning it in the lathe. That worked but was very slow and shook the lathe a lot. By far the best way was to just saw it in a vice with the hacksaw.

I drilled the hole down the middle on the lathe. I had trouble centering the pilot drill. You are supposed to use a special center drill as described [here](#), but I don't have one of those so I used the surprising technique called "catching the centre". Here are a couple of excellent videos I found that describe this technique: -

Once I had got the drill started I put the chuck back in the tailstock and drilled the full length with 1mm, 2mm and 3mm drills.

Here are the finished bearings :-



The RepRap instructions suggest that the bearings should be made after the spindle but I think it is better to do it the other way round. That way you can try the bearings against the spindle while it is still in the lathe and turn the spindle down to the right fit.

# Steady as she goes

Sunday, 22nd July 2007 by Nophead

I can confirm my homemade "three point steady" does work, I made this with it :-



It's the RepRap extruder drive screw which fits in the bearings shown in my last post. The RepRap instructions say to use a blow torch and plumber's flux to attach the steel cable but I found it easier to use a soldering iron and electrical solder.

Here it is installed with a small G-clamp in place of the top half of the pump :-



And here is a video of it being tested with a variable DC power supply until it shed the clamp :-

# Boring

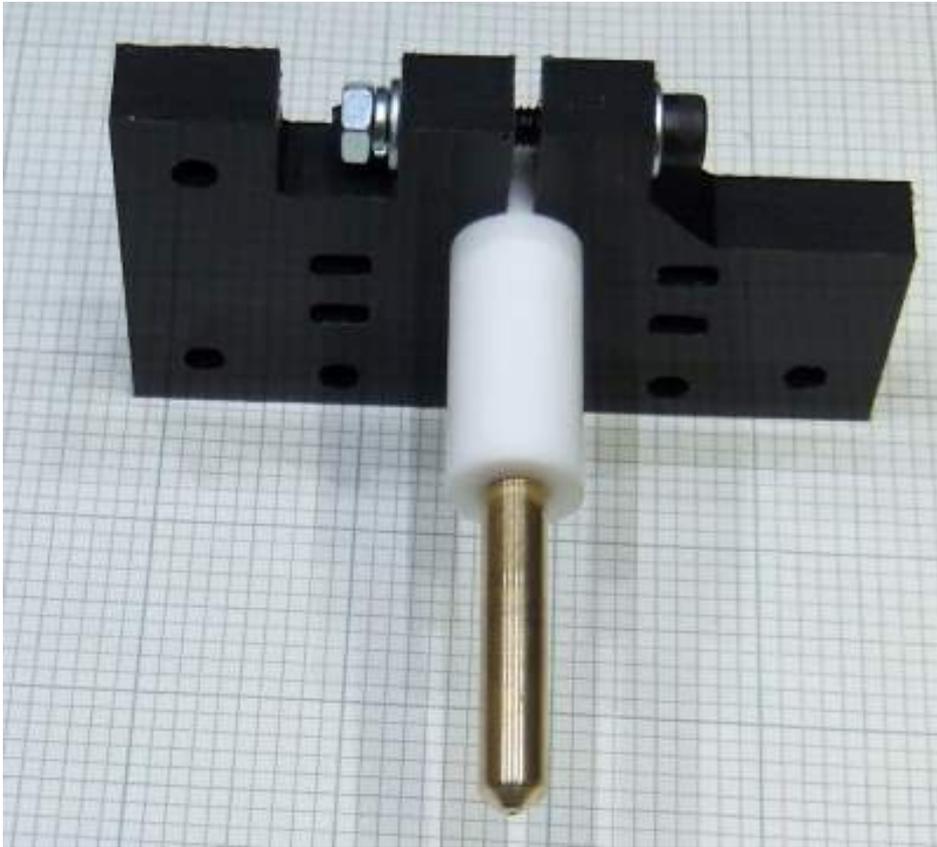
Monday, 23rd July 2007 by Nophead

Well turning, boring and tapping to be precise. I made the extruder nozzle and PTFE heat barrier this evening :-



I am making a mixture of an older RepRap design and the latest, mainly because I bought the parts before the design was changed. I made a small modification to the nozzle design. You are supposed to use a bottoming tap to thread the inside of the PTFE tube. As I don't have one of those, I drilled the hole 5mm deeper to accommodate the tapered end of the tap. I also turned the last 5mm of the nozzle down instead of threading it. I should have made the PTFE tube 5mm longer but I forgot so I have slightly less heat barrier.

I am not totally happy with the nozzle because I bent it while I was threading it with a die. I don't think it will affect the operation it just looks a bit scrappy. Here they are screwed together and inserted into the clamp :-

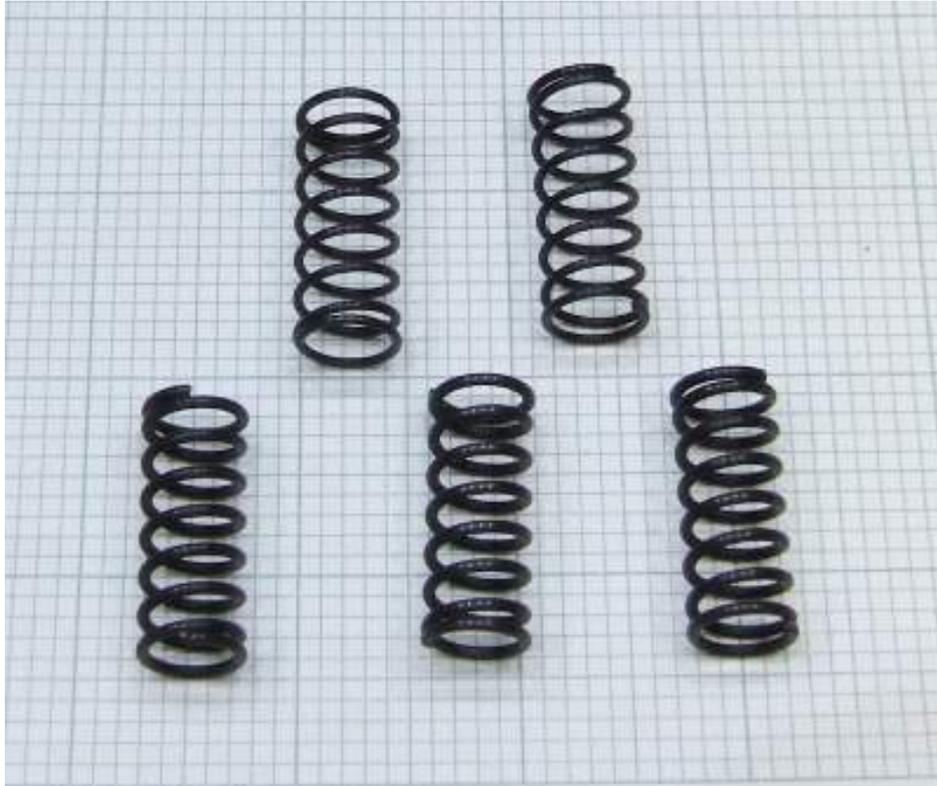


I need to add the heating element next.

# Well sprung

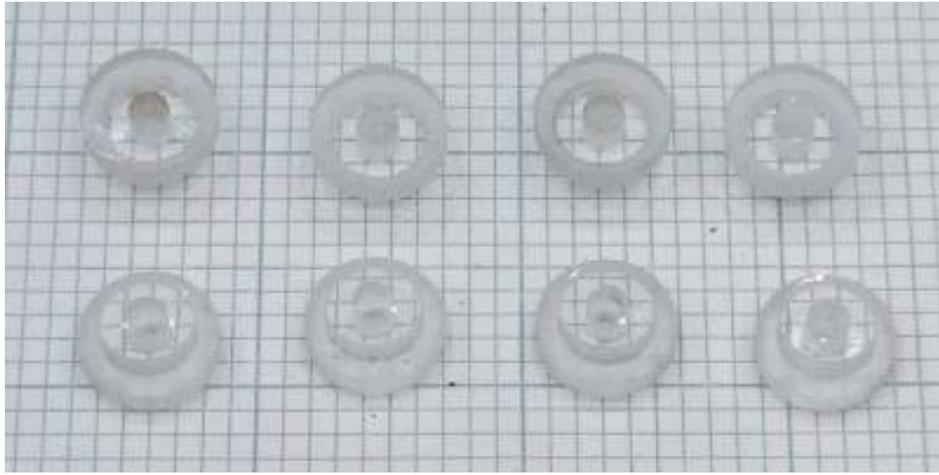
Wednesday, 25th July 2007 by Nophead

Some versions of the RepRap FDM extruder use four springs to press the filament against the threaded rod. The latest version uses compressed plastic piping but I read somewhere that it loses its tension over time. When I was dismantling the CD player out of my Jukebox the other day I came across five reasonably powerful springs :-



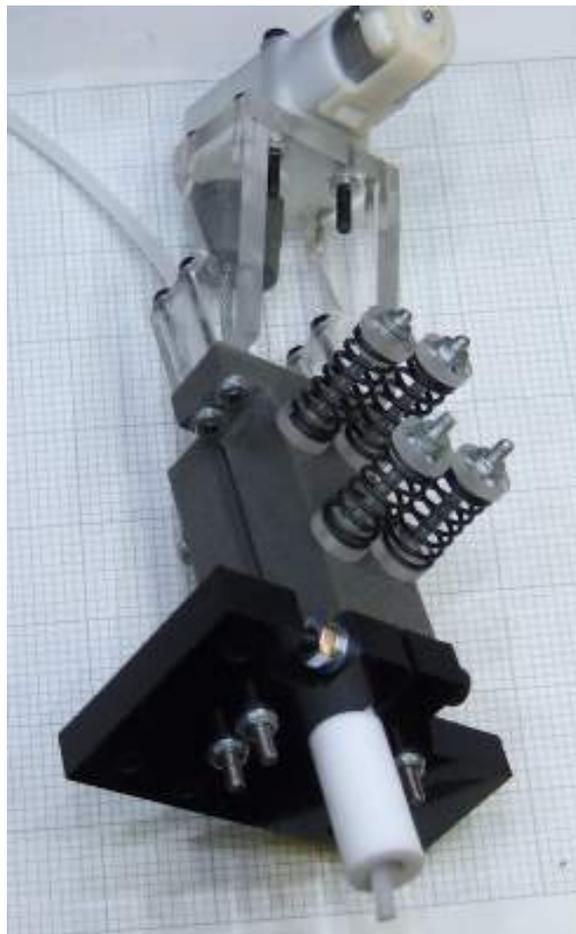
Unfortunately the two at the back are not as strong as the front three. However, Forrest Higgs has shown with his Tommelise machine that you can get away with just two springs at the top so I will put the weaker ones at the bottom.

Another problem is that the springs are too big in diameter so I made some stepped washers out of Perspex to fit in the ends. As eight were needed this was the biggest run of things I have milled so far. It was a good way of using up all the scraps of Perspex left in between things I have milled previously. The only problem was that a few disappeared up the vacuum cleaner and had to be retrieved from the bag!



I was worried about the friction in my extruder channel so I tried polishing it with metal polish. This worked very well and greatly reduced the friction. A friend just happened to give me a spray can of PTFE dry film spray today so I gave it some of that as well.

I put the pump together minus the barrel and checked that it can move HDPE filament. It remains to be seen if it can extrude it.



# Hotting up

Tuesday, 31st July 2007 by Nophead

The latest RepRap heater design consists of insulated nichrome wire wound around a threaded barrel and then stuck down with a coating of J-B Weld high temperature epoxy. I think that is a good way to do it but the insulated nichrome is expensive and I happen to have some nichrome from a heating element. It came from an old hair dryer I think.



Luckily it seems to be the right gauge to give me a reasonable number of turns. The spec was for 8 ohms which gives a maximum wattage of 18W at 12V. That gave me a length of about 340 mm which made 17 turns. I attached some tinned copper tails to make the connections easier to handle. I tied them to the nichrome and then soldered it. On reflection that was probably a bad idea as the solder does not stick to nichrome so if it oxidizes it may go open circuit. Small crimps would be a better I think.

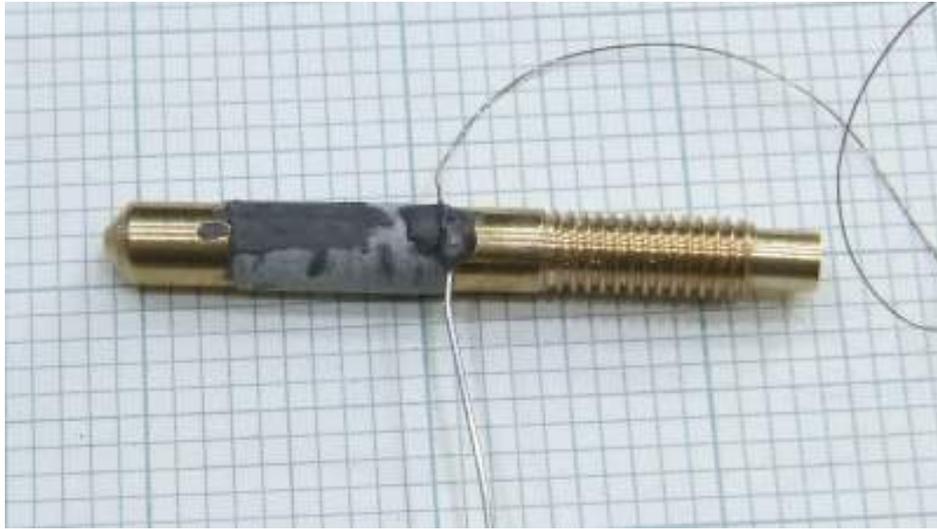
I started by laying down a layer of J-B Weld to insulate the barrel.



After letting this dry for 24 hours I put it in the lathe and turned it down to as thin a layer as I could get before it started flaking off. That was at about 0.2mm.



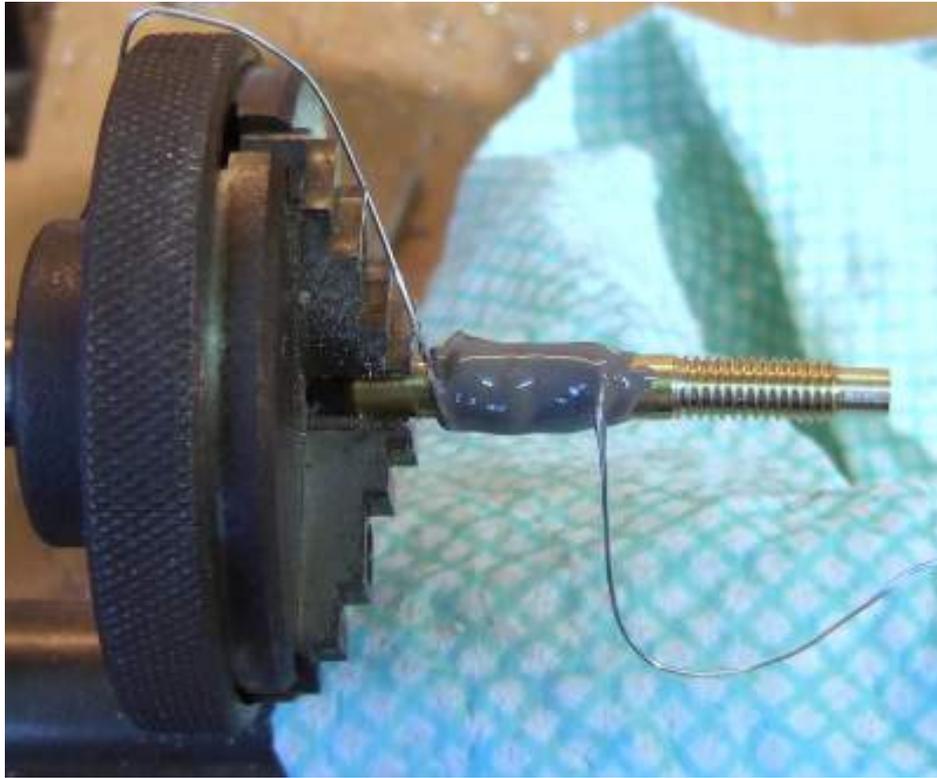
I added some more J-B Weld to repair the gaps and also used it to attach one end of the nichrome.



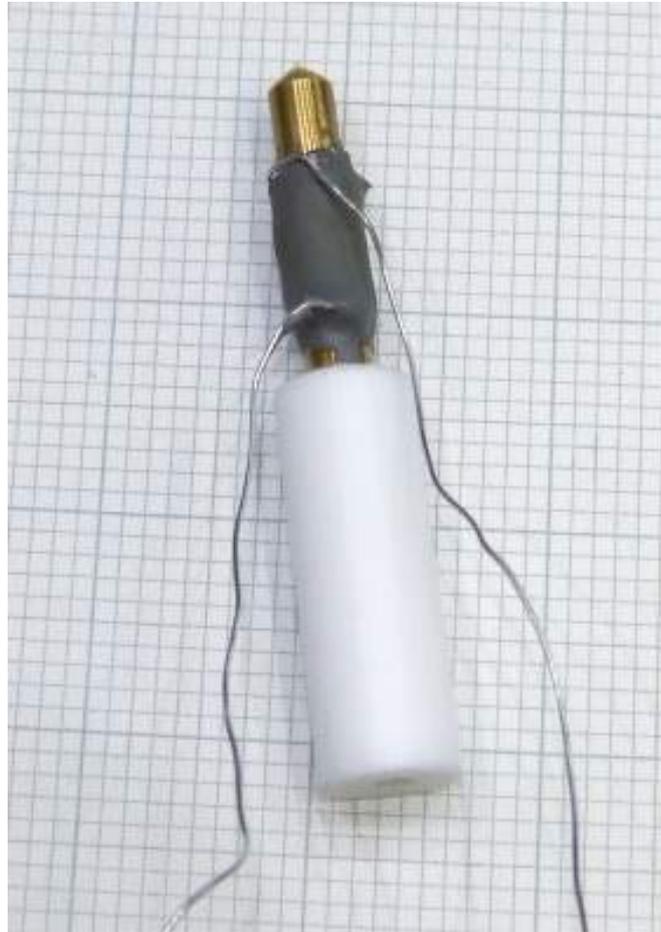
After another 24 hours I put it back in the lathe to make the winding.



Finally I added another thick layer of J-B Weld and left it another 24 hours to set. A very slow way of doing it compared to using insulated nichrome and a single coat of J-B Weld.



I tested it by putting a thermocouple probe down the barrel and running it from a variable bench power supply. I heated it up to 200 °C at which point it smoked a bit and the J-B Weld started to discolour. I dropped it back down to 160 °C which only required about 5W of power and pushed some HDPE filament down it. Pressing as hard as I could I got it to extrude some 0.75mm diameter filament though the 0.5mm hole in the nozzle. You can just see a little bit poking out in the picture of the finished article below :-



I don't know how long it will last, the J-B Weld may crack as there is nowhere for the nichrome to expand to. Insulated nichrome would be better in this respect.

There should also be a glass bead thermistor attached to the nozzle to monitor the temperature so that it can be regulated in software. Having seen the resistance of copper stepper motor coils increase noticeably when they get hot, and tungsten light bulb filaments change resistance by a factor of ten, I thought I should try using the resistance of the heater to measure its temperature. The resistance didn't seem to change much so I looked up the temperature coefficient and found it was much lower than other metals, so that is a non starter. I have ordered a couple of thermistors but they are out of stock at the moment so I will have to run it open loop to start with.

The next thing to do is put the pump back together and see if it can extrude.

# Roll out the barrel

Tuesday, 7th August 2007 by Nophead

I don't seem to have achieved much in the last week as I have been waiting for a few things to arrive. I have managed to mount the extruder on the bottom bracket that previously held the milling drill. I had planned to do that to make it easy to swap between the two, so I used a smaller diameter PTFE rod for the thermal barrier to allow it to fit through the same hole as the drill. What I forgot was that the wires would also have to pass through the same hole! It is a tight squeeze as you can see. The heater wires actually have some plastic insulation where they pass through the aluminium, I hope it doesn't melt!



Another thing I forgot to allow for is that I had to mount the extruder clamp on standoffs to clear the bolt heads and leave space for the wires to exit. Unfortunately that means the nozzle doesn't quite reach the XY table so whatever base material I decide to extrude onto will have to be at least 5mm thick.

On the left of the nozzle you can just see a small thermistor to measure its temperature. The recommended part from RS is on back order but one of my fellow reappers called englewood was kind enough to send me the alternative one you can see. I hope to repay him with some HDPE extruder parts if my machine is successful at making them.

I attached it by filing a flat on the barrel and clipping it with a couple of coils cut from a small spring. I used a little thermal grease between the two.

The next step is to calibrate the thermistor and see if it will extrude.

# Knobby nuts

Thursday, 9th August 2007 by Nophead

Having assembled and dismantled my extruder a few times I found it quite fiddly and time consuming. The reason being is that all the fasteners need either an Allen key and a spanner or two spanners. I solved this by placing shake proof washers between the screw heads and the plain washers that are there for load spreading. Only problem was I had to buy them in packs of 250 so I have enough to last the rest of my life!



The result is that once the bolts are finger tight the washers bite and hold the head so only one spanner is required to tighten the nuts.

The nuts that tighten the springs were still a bit tedious. This is because they need tightening a long way down the thread to tension the spring and you need a spanner all the way because the springs are stiff. Wing nuts are the obvious answer but I didn't have any and I am not sure whether there is room to spin them. Instead, I milled some knobs out of Perspex and tapped them to act as nuts. I have christened them knobby nuts but that probably only strikes a chord with people in the UK.

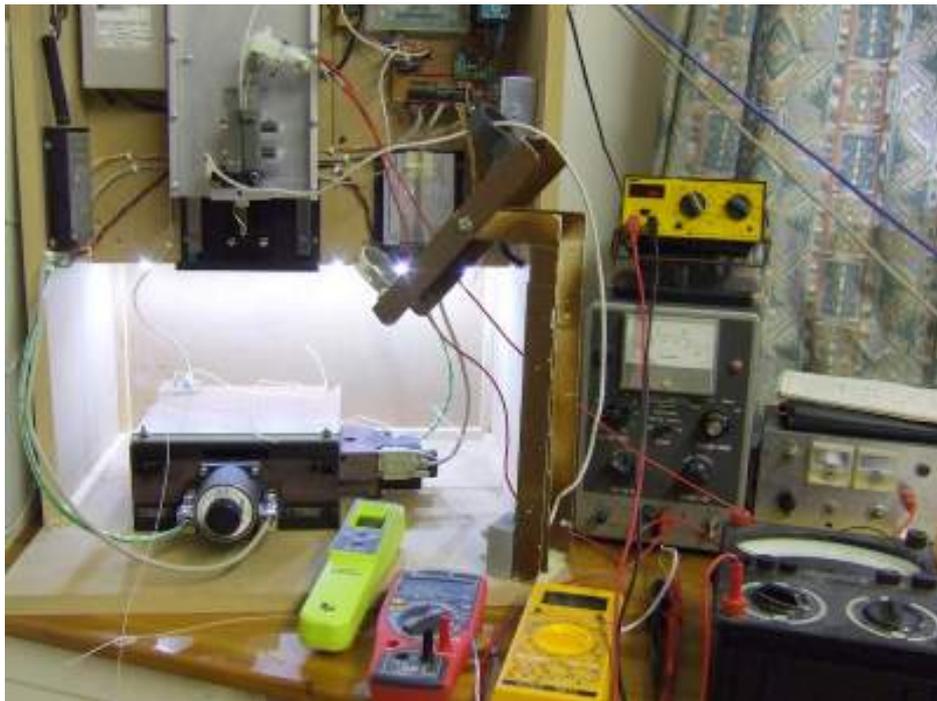


# Thermals

Saturday, 11th August 2007 by Nophead

I need to knock up a controller for the extruder. This will take commands from the main controller via an I<sup>2</sup>C bus and control the motor speed and heater temperature. It may also need to control a fan to cool the workpiece and monitor a filament out detector.

I decided to drive the extruder with bench power supplies to see if it works first and get an idea of its parameters and hence the requirements for the controller. Here is my test setup :-



As you can see I have plenty of meters. I have been hoarding them for years but it is not often I get to use more than two at a time. Here I am measuring extruder voltage and current, temperature and thermistor resistance. I have another three or four about somewhere but I doubt I will ever need to measure 8 parameters!

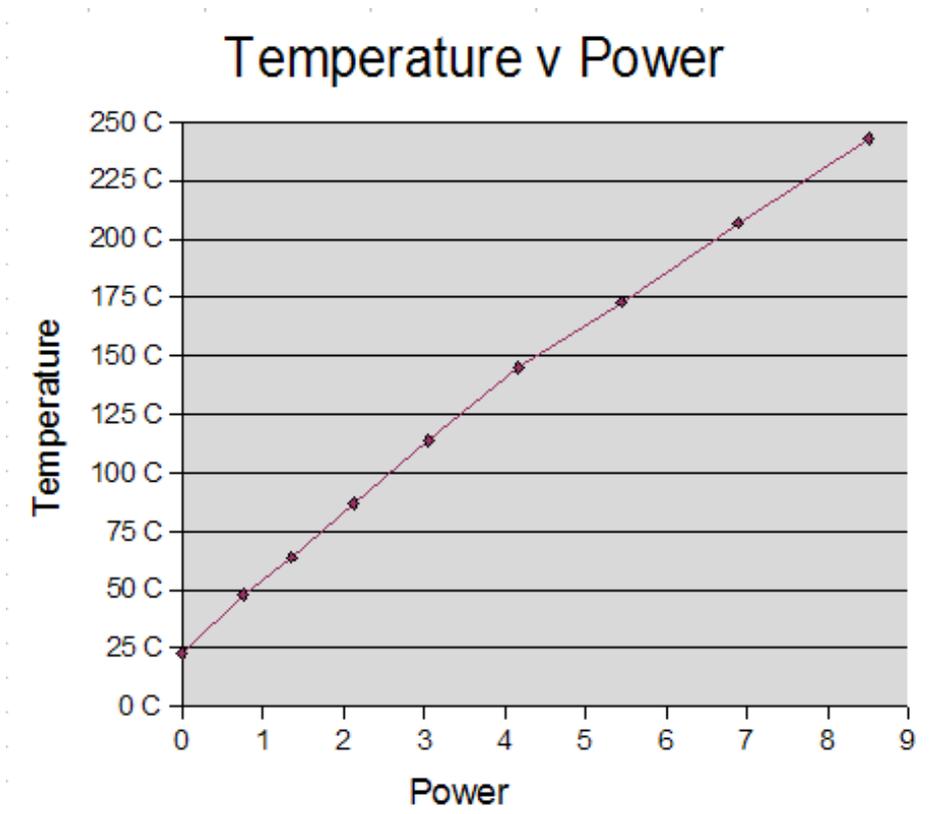
The bench power supplies are ancient, I think the big one has valves in it and I built the small one when I was a child. I had a near perfect memory then so I never saw a need to label anything. I have several other items of equipment from that era, including an oscilloscope, with no labels on anything.

Here is the raw data I measured :-

Power	Temperature	Resistance
0 W	23 C	2108 R
0.77 W	48 C	897 R

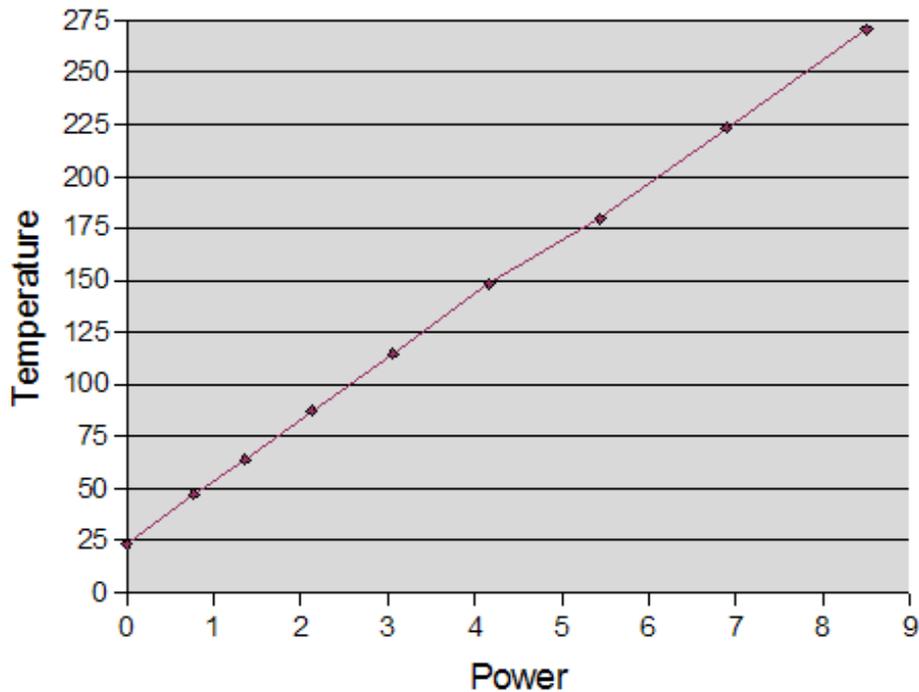
1.36 W	64 C	533 R
2.13 W	87 C	280 R
3.06 W	114 C	145 R
4.17 W	145 C	73 R
5.44 W	173 C	42 R
6.89 W	207 C	21.9 R
8.5 W	243 C	12.2 R

I plotted a graph of temperature against power. I expected it to be a straight line because the rate of heat loss is proportional to the temperature difference between the nozzle and its surroundings and at equilibrium that must equal the input power.



As you can see it is a bent line with a change of gradient at 150°C which I can't explain. I measured the temperature with a thermocouple inside the barrel. It is rated for use up to 250°C but the strange thing is that if I plot a graph of the temperature indicated by the thermistor then the graph is much straighter. I calculated the thermistor parameters from the thermocouple data ignoring the last three points.

## Adjusted Temp V Power



So I am not sure what to make of it. I may have to repeat the experiment with my IR thermometer. As long as the thermistor measurements are repeatable I don't suppose absolute accuracy is necessary, other than to swap setting with other RepRappers.

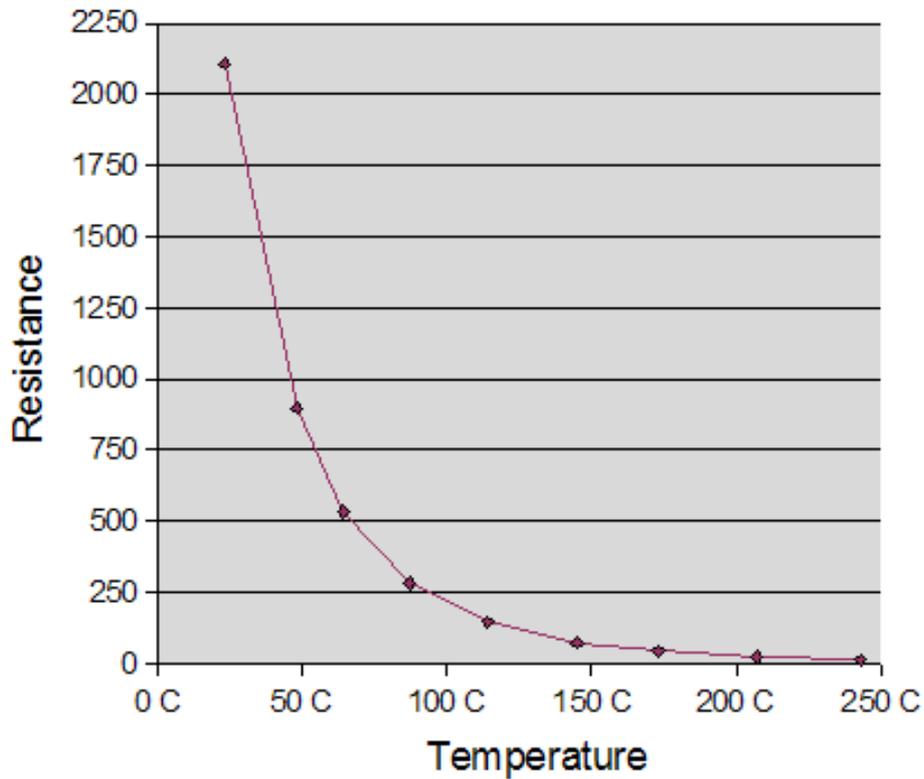
The thermistor resistance is a extremely non linear. Its is approximated by a negative exponential of the reciprocal of absolute temperature.

$$R = R_0 e^{B \cdot (1/T - 1/T_0)}$$

$R_0$  is resistance at known temperature  $T_0$ , in my case room temperature, expressed in Kelvin. Beta is a second parameter of the thermistor which can be calculated if you know the resistance at two different temperatures. I calculated it for each of the first six power levels and then took an average. It's probably not a very accurate value because the thermistor, being on the outside of the barrel, was probably at a significantly lower temperature than the thermocouple on the inside. However, it is the inside temperature I am interested in so I probably get a value of beta that sort of compensates for that.

Here is the graph of resistance against temperature :-

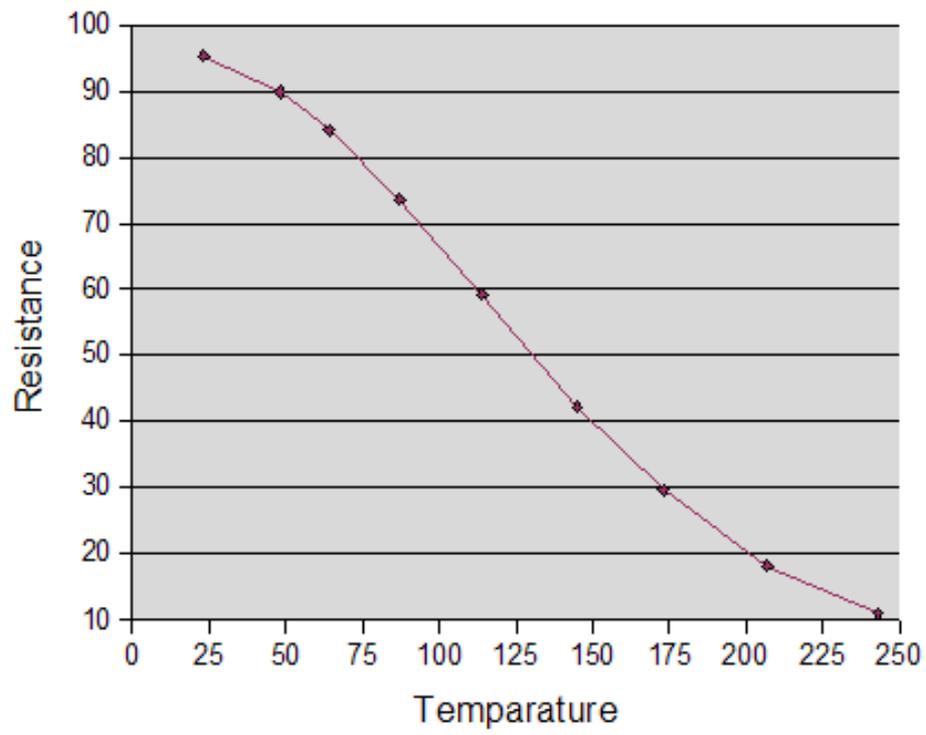
## Resistance V Temperature



I plan to measure this with the analogue to digital converter in the MSP430 micros I am using. The problem is to cover such a large resistance range would end up with very little accuracy at the high temperature end where the machine will operate.

I had an idea that putting a fixed resistor in parallel would close up the bottom end without affecting the top much. Indeed it does, here is a graph of the combined resistance against temperature with a 100 Ohm resistor in parallel. You can see it is not far off being a straight line, much easier to digitise accurately.

## Combined Resistance v Temp



# Sore thumbs

Sunday, 12th August 2007 by Nophead

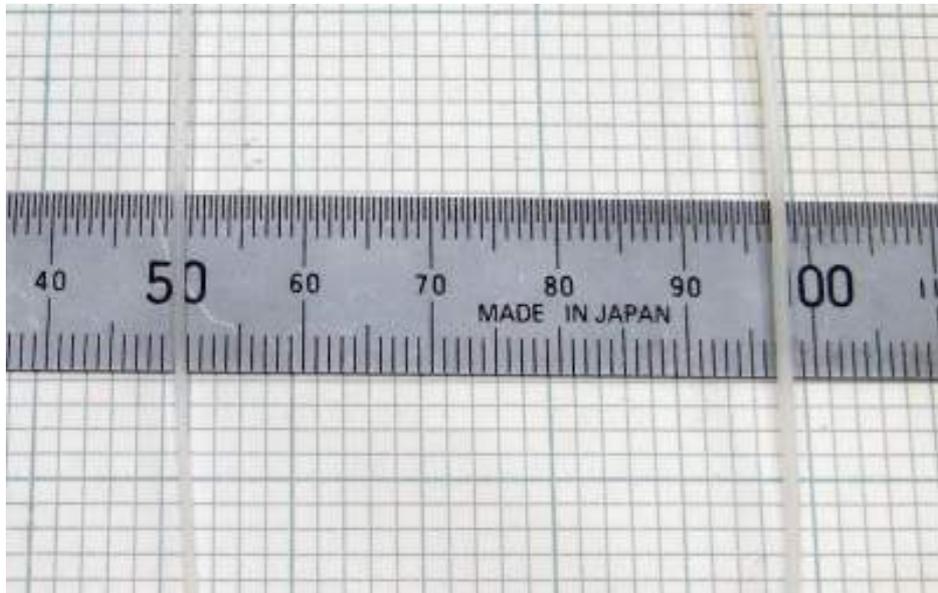
Well thumbs and fingers actually through stripping down and rebuilding my extruder a few times to solve teething problems. It has actually taken me a couple of days to get it working reliably. There were only two problems really :-

The first was that I was not tightening the springs enough. My springs are bigger diameter than the recommended ones and are too stiff to compress with ones fingers but even so I need to have them fully compressed for the extruder not to jam. What happens when they are not tight enough is that the screw thread slips against the filament and starts grinding it away instead of moving it.

The biggest problem was that my soldered joint between the steel cable and the drive screw kept breaking. The reason being that the drive screw is stainless steel which can not be soldered with normal flux. I tried cutting a cross in the end of the screw to give the solder something to hold onto. That did not work because the solder just forms a bead that does not penetrate the slots.

In the end I stuck it with JB Weld. For some reason it does not cure properly in the recommended 15 hours so I transfered it to the oven and baked it for 2 hours at gas mark 6. That seems to have done the trick.

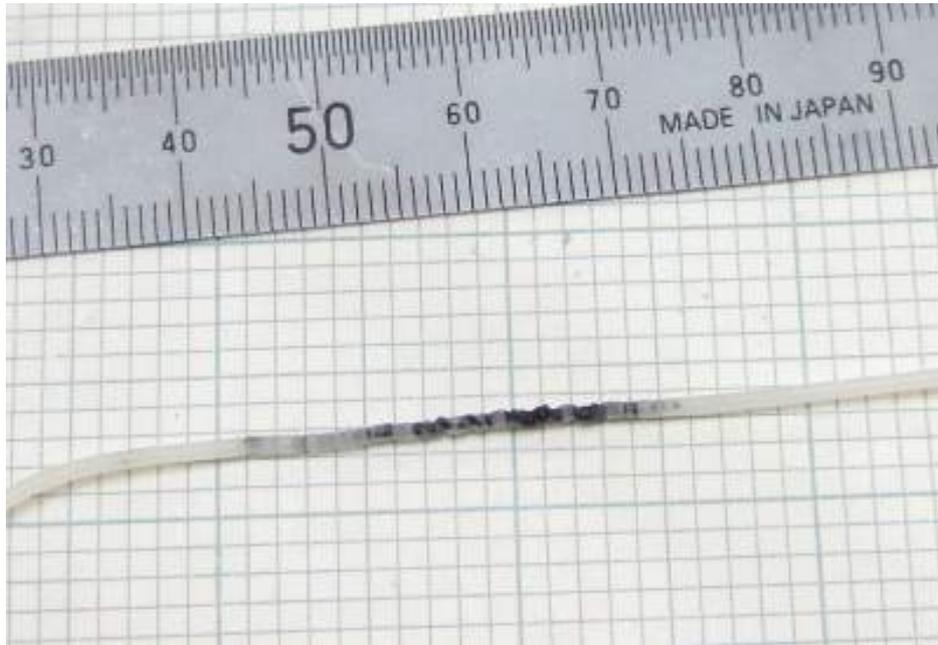
I have found that running the extruder at different speeds gives different sized filaments.



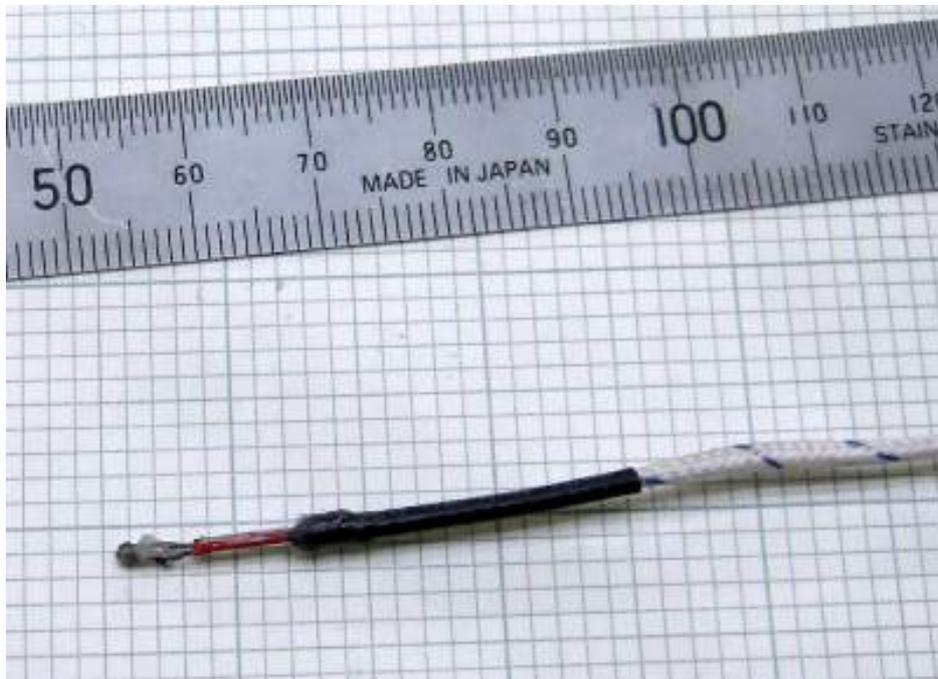
The one on the left was extruded with the motor running from 4V and is about 0.8mm and the one on the right was extruded with the motor running from 10V and is 1.2mm. They are both extruded from a 0.5mm hole. I think what happens is that the plastic is compressed as it enters the hole and expands as it leaves it. The faster the motor runs the higher the pressure so the more it contracts

and expands. The strange thing is that other people have not seen this effect. Possibly the hole in my nozzle is too deep or too shallow, I am not sure which.

I was surprised when I saw this piece emerge :-



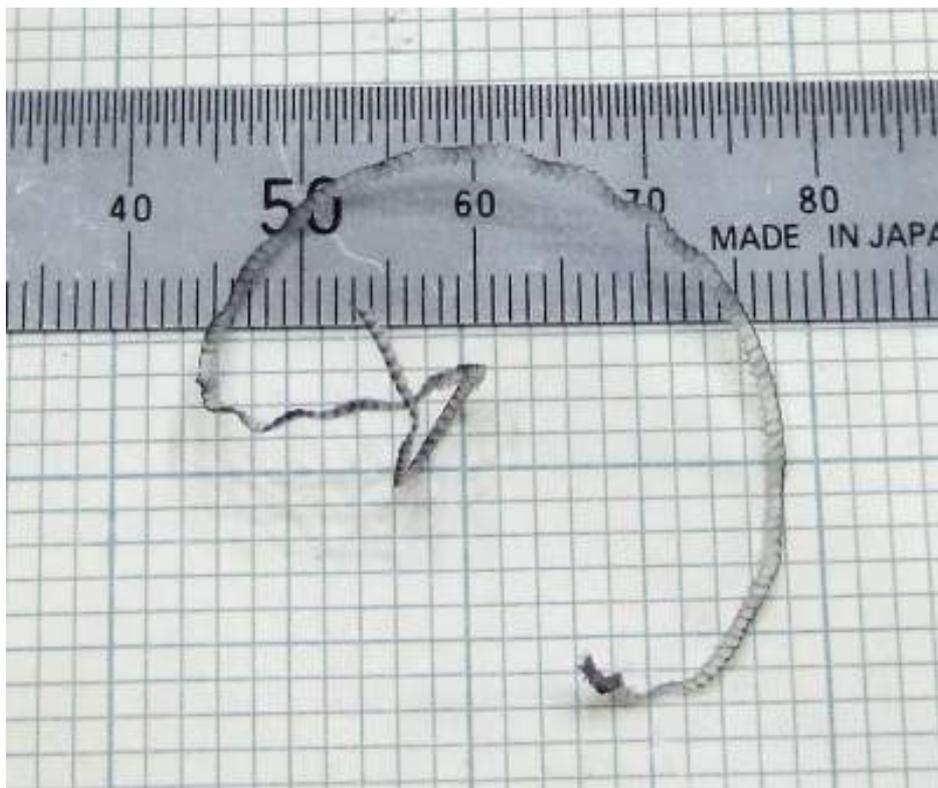
But not when I examined the thermocouple I had used to measure the temperature of the molten plastic :-



It is supposed to work up to 250°C but it looks like the heatshrink sleeving they used is not up to the job.

My extruder occasionally produces swarf from the gap between the pump and the clamp. I am not

sure of the exact mechanism for this is but it does not seem to affect its operation.



Here is a video of the extruder in operation and the filament produced showing self organising behaviour.

# All wound up

Friday, 17th August 2007 by Nophead

My years of hoarding junk is finally starting to pay dividends. I decided to address how I was going to feed the filament to my extruder. It only uses it slowly but when it runs out you have to strip down the extruder to start off a new piece. HDPE comes on a big 5 Kg reel like this :-



I thought it was asking a bit much for the extruder to rotate something that big and heavy so I started to look round for a smaller reel. I came up with this :-

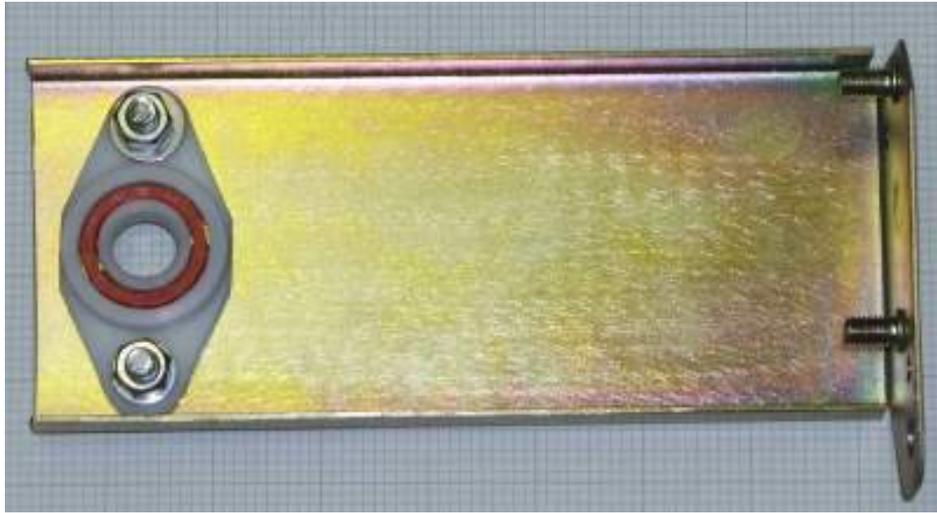


It is a reel of 10000 4.7V zener diodes which I rescued from a skip. I removed the diodes, if anybody wants an envelope full just ask. It is about 270mm diameter, 70mm wide with an internal diameter of 70mm and a 30mm hole for a spindle. I wound some HDPE on to it and found that despite it being a lot smaller and lighter than the original reel it holds almost exactly half the plastic, i.e. 2.5Kg. The only problem I might have is that the plastic is quite tightly curled on the inside. Hopefully the extruder will have enough pull to straighten it.

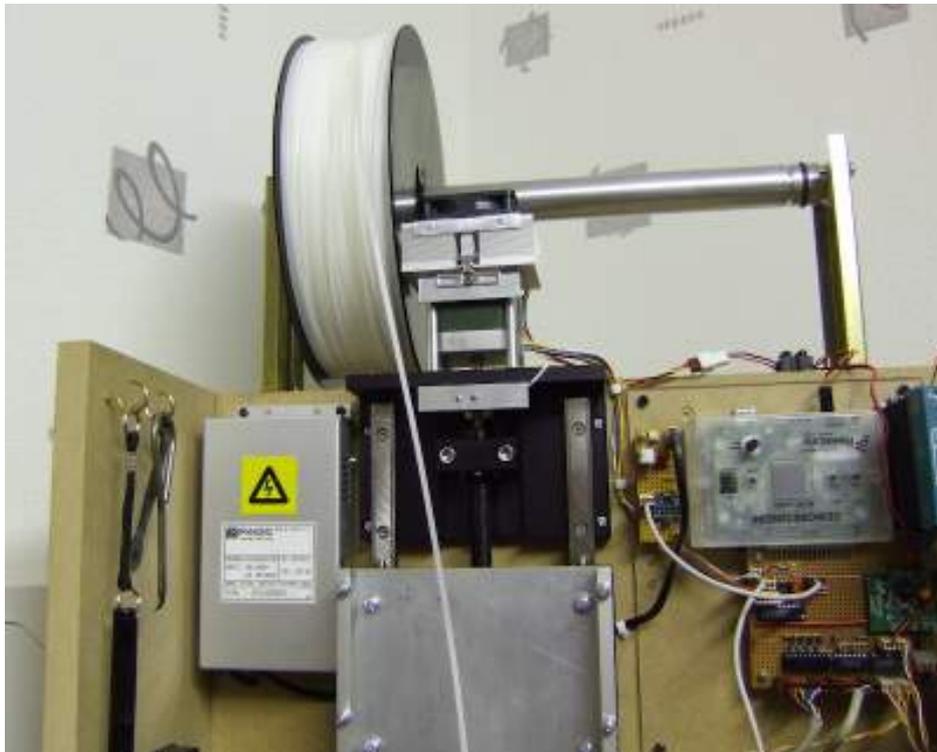
So a plan was forming, I just needed an axle with descent bearings. Another piece of junk I had rescued from a skip was this aluminium roller:-



It was exactly the right diameter and was mounted inside a metal housing with ball bearings. I chopped up the housing to make two mounting brackets and moved the bearings around.

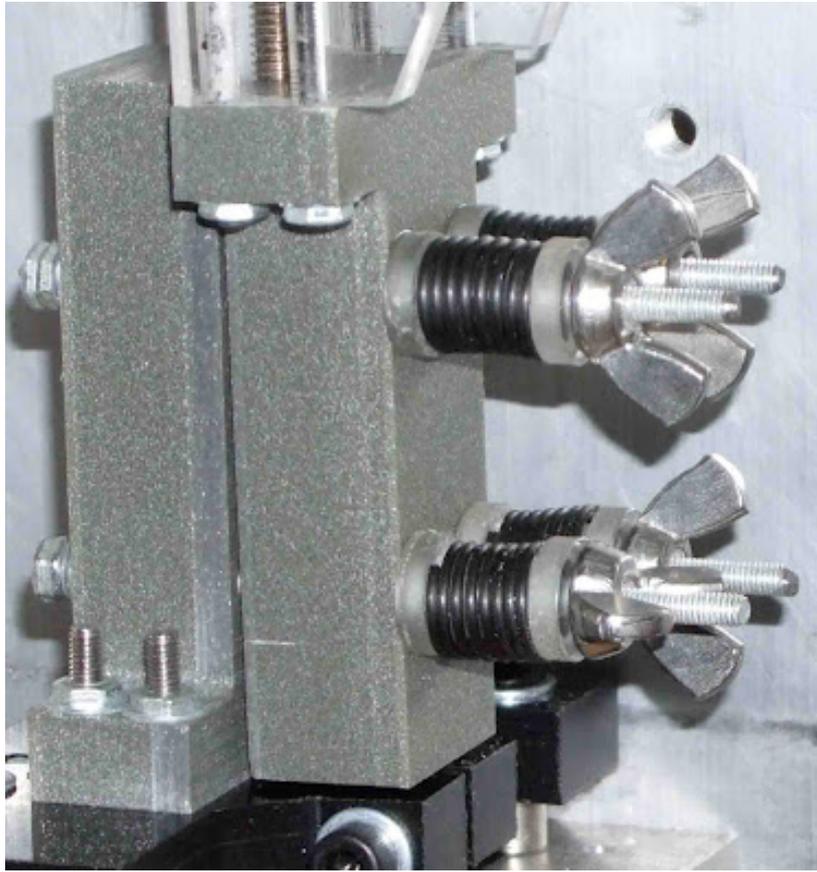


All that was left to do was screw it to the top of my machine. The roller is a bit long for an axle but it was easier to leave it full length than cut it and turn the end back down to fit the bearing. My lathe is nowhere near big enough for that. Here it is mounted up :-



I even managed to re-use the rubber 'O' rings on the roller to hold the reel in place. The bearings are so good that a quick twist will leave it spinning for more than 30 seconds so the extruder has no problem dragging the filament off.

Finally I replaced the knobs that I made with proper wing nuts as they are easier on the fingers.

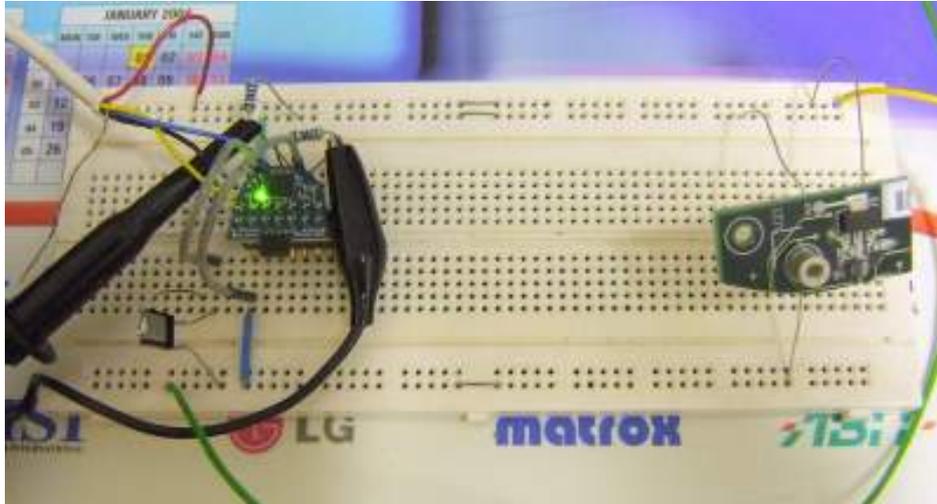


The next task is to design the electronics to drive the extruder.

# Heatwave

Sunday, 19th August 2007 by Nophead

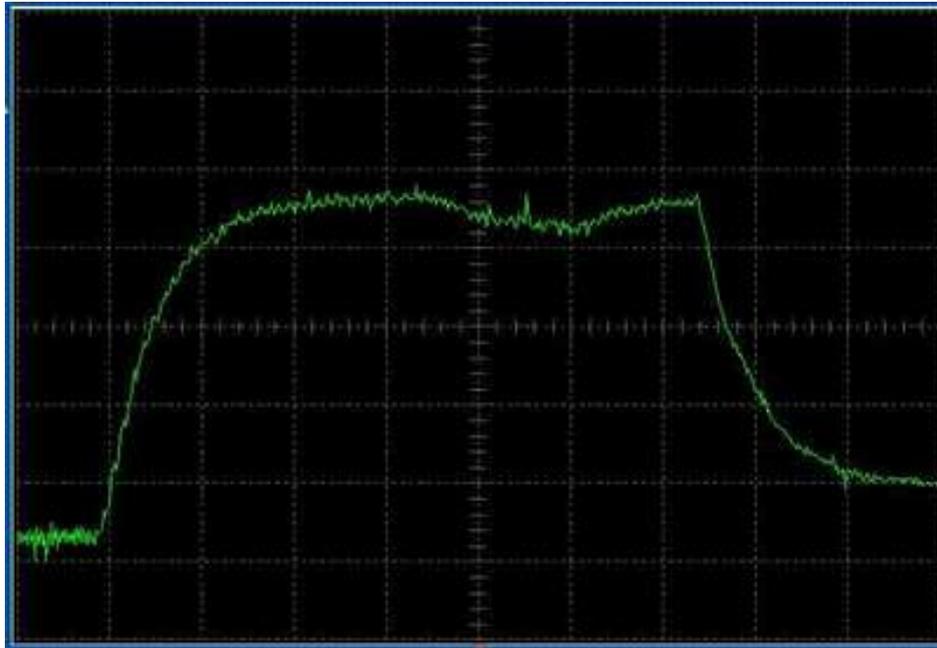
I made a start on my extruder controller, on breadboard, as it is a bit experimental. As you can see it's a strange mixture of surface mount and through hole technologies!



The little PCB on the far right is a 3.3V regulator which I hacked out of a scrap PCB complete with all its decoupling caps. It had three handy vias for the three connections I had to make. The rest of the parts are the heater controller. The circuit could not be simpler. The heater is switched with a BTS134 protected MOSFET. Even with only a 3.3V gate drive its on resistance is so low it does not even get warm when switching about 1.5A.

The thermistor is just wired to a potential divider which gives 0.6V with an impedance of 100 . That makes a voltage that varies almost linearly with temperatures between 20°C and 200°C that can go straight into an analogue channel on the MSP430F2013. The micro can also measure its own supply voltage so that can be used to null out the supply tolerance.

Here is a graph of voltage on the input, inverted as it is an NTC thermistor, so it is roughly a graph of temperature :-



The heater was driven with a fixed 50% PWM drive. The temperature rises exponentially until it reaches equilibrium after about 12 minutes. I then turned on the motor and let it extrude some plastic. You can see the temperature drops significantly and rises again when I stopped the motor. This is because the hot plastic leaving the extruder carries heat away with it. Because plastic has a very high specific heat capacity this effect is significant. Finally the temperature falls exponentially when the heater is switched off.

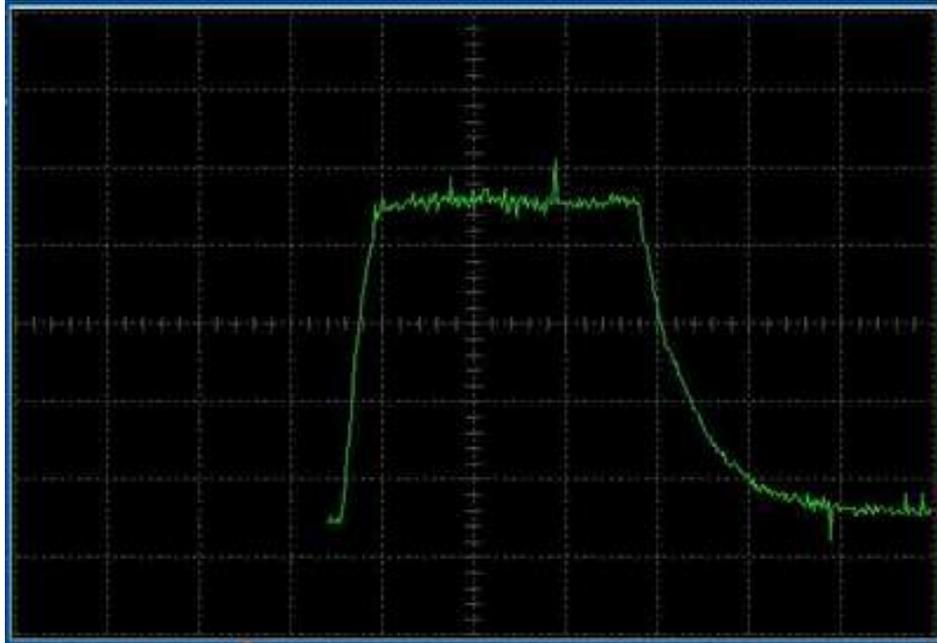
The graph shows why closed loop control is necessary. The rise will be much faster because full power will be applied until the target temperature is met. That will reduce the warm up time considerably. I also hope to reduce the sag that happens when extruding which will make the extruded filament more consistent.

So a little bit of software now to close the loop.

# Bang bang

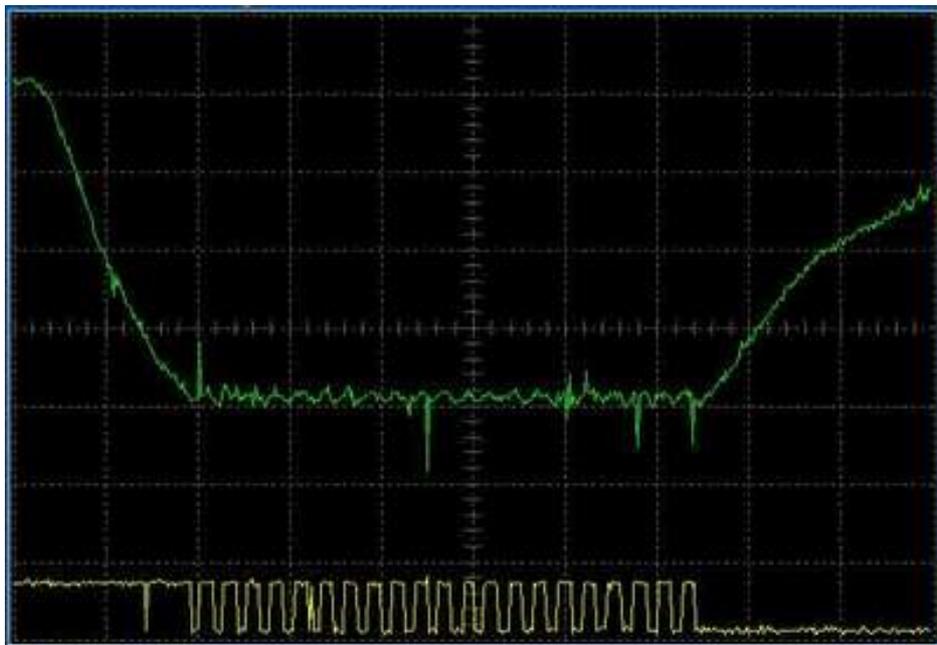
Monday, 20th August 2007 by Nophead

I implemented the simplest form of temperature control, known as bang bang control, which is just turn the heater on if it is too cold and turn it off when it is too hot. This seems to work well, here is graph to compare with the last post. The time divisions are 4 minutes.



The warm up time has reduced from about 10 minutes to just over 1.5 minutes and you can't really notice any change in temperature while it was extruding.

Here is a graph on a faster time base of 1 minute per division showing the heater control signal. This one has not been inverted so temperature is upside down.



As you can see there is some ripple on the temperature of the order of about 10°C. I could probably improve that with PID control but I don't know if it will make much difference to the build quality. I might do it as an exercise out of interest as I have not implemented PID before.

There is a lot of noise in the system, which is not surprising with wires all over the place. It should get better when I make a PCB or veroboard version and mount it near the extruder. Fortunately glitches don't really matter because the thermal time constant smooths it all out.

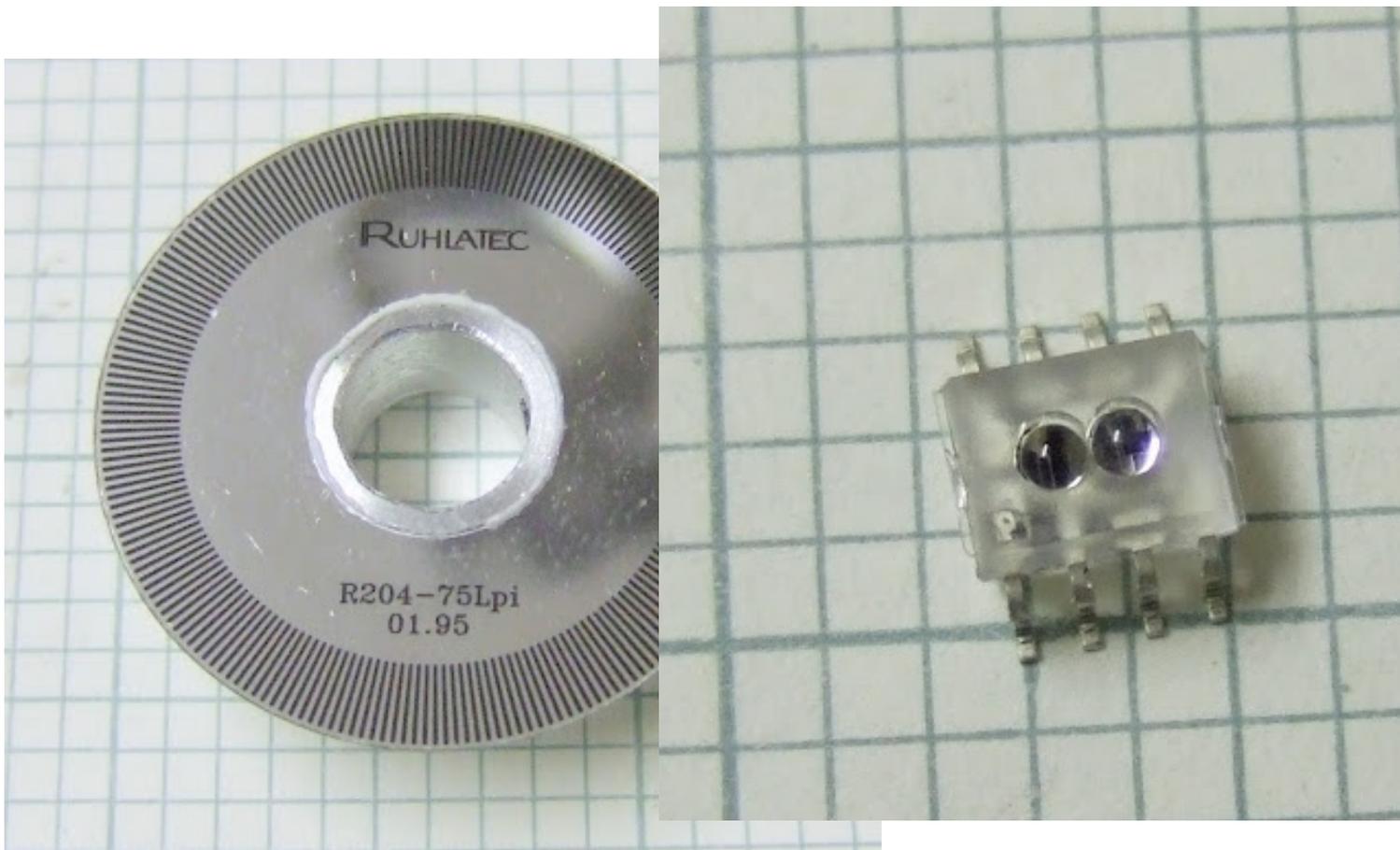
The next task is to link it to the main controller and see if I can get accurate temperature readings back from it.

# RPM

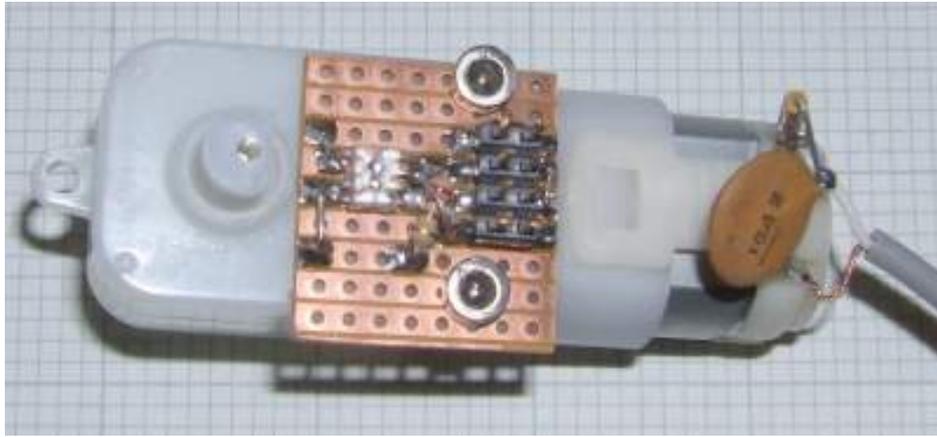
Friday, 31st August 2007 by Nophead

While testing my extruder I found that the filament diameter seems to vary with temperature and pressure. I wanted to investigate this further so I decided to add a shaft encoder to the output of the small gear motor which drives the polymer pump. This would allow me to regulate the speed precisely because the micro would know the exact position of the shaft at any instant.

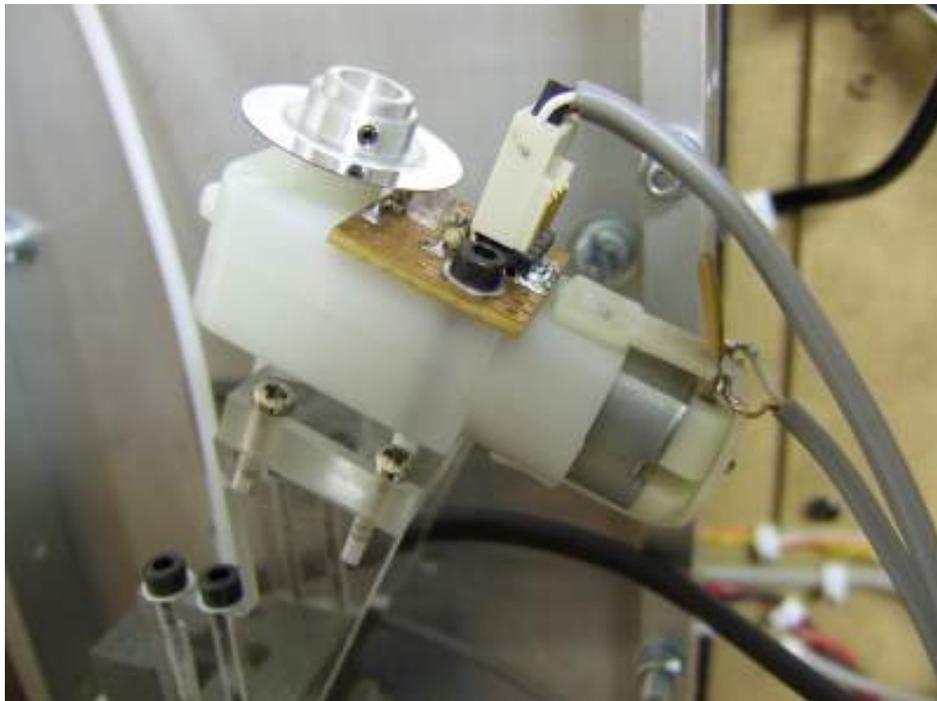
My first thought was to use a magnetic shaft encoder such as the [AS5035](#) but then I remembered I had an evaluation kit for some HP reflective optical encoders which I had saved since 1995. HP are no longer in the semiconductor business, that part of the business became Agilent and these chips have been passed on to Avago. The kit had a linear encoder strip, a rotary encoder wheel and three sensor chips.



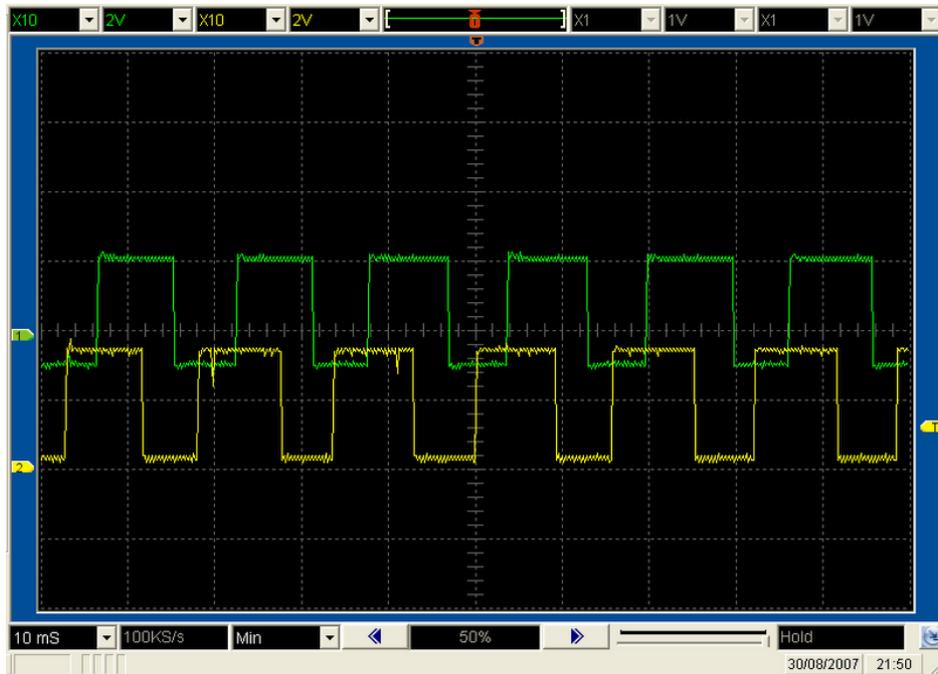
One of the advantages of magnetic encoders is that they don't need such precise alignment as the optical ones. However, in my case I would have needed to build a raised mounting to hold it over the end of the shaft, whereas the optical encoder can be mounted flush against the gearbox. Here is another bizarre mix of surface mount and through hole components. Can you spot the SMT decoupling cap?



I doubt that I have complied with the strict mounting tolerances but it seems to work well enough for this purpose. Here it is with the code wheel in place :-

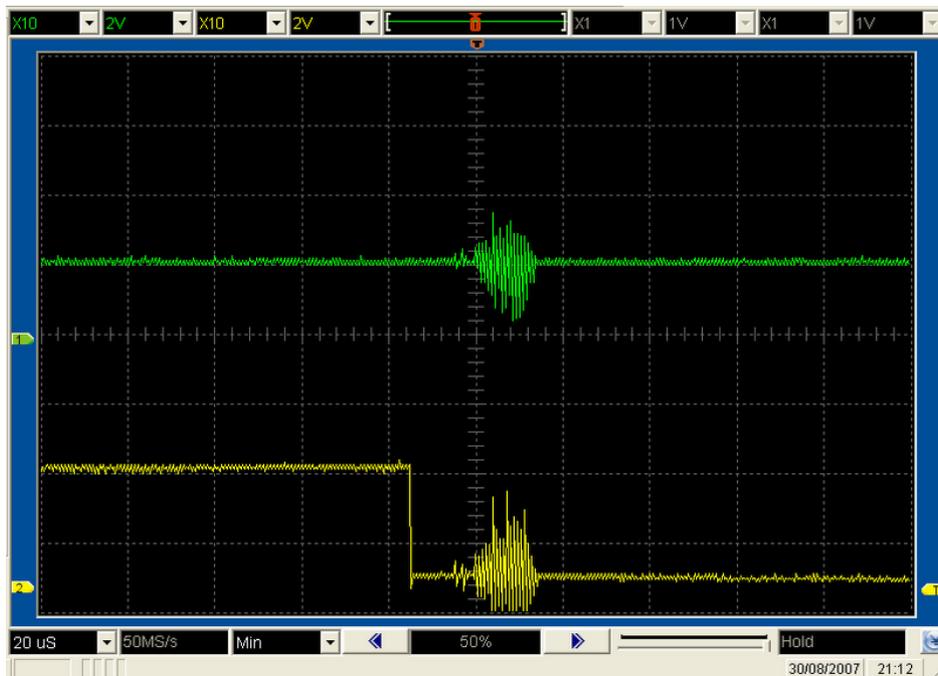


Here is what the outputs look like when the shaft is turning :-

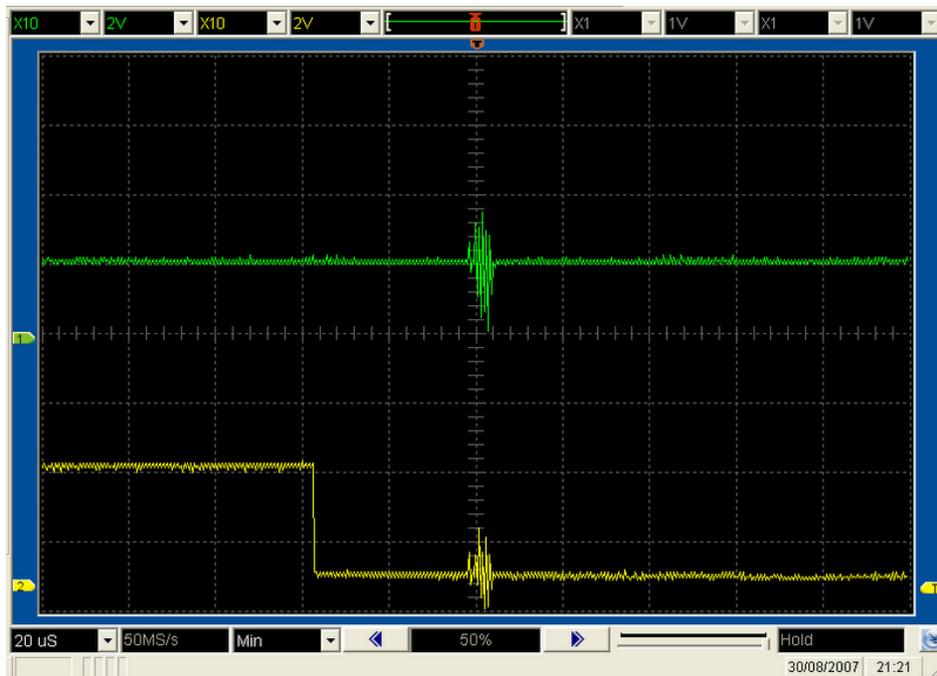


Two square waves are produced which are  $90^\circ$  out of phase with each other. This is known as quadrature encoding and it allows both the distance and direction of movement to be determined. I would have expected the mark space ratio to be more equal but it is probably out of spec due to me not meeting the alignment tolerances.

Notice also the nasty glitches on the bottom trace. These are commutation noise from the DC motor despite having a 100nF capacitor close to it and using screened cables. Here is what the noise looks like close up without the capacitor :-



And this is the improvement with the capacitor fitted:-



I also tried adding a resistor to form an RC snubber and adding a ferrite ring around the motor cable, but both made it worse. The only way to effectively suppress DC motors is to mount suppression components directly across the armature windings, i.e. the other side of the brushes.

So stuck with that much noise, it was impossible to use an edge triggered interrupt approach, so I polled the inputs from a fast interrupt and debounced them in software. Here is the code :-

```
//
// Process the shaft encoder signals
//
#define DEBOUNCE 3
static void scan_optos(void)
{
static byte last_raw = 0;
static byte debounce_count = DEBOUNCE;
byte    delta;

//
// Debounce the inputs
//
byte bits = P1IN & (SHAFT_A | SHAFT_B);
if(bits != last_raw) {
    last_raw = bits;
    debounce_count = DEBOUNCE;
    return;                                     // Still changing
}
if(debounce_count)                             // Still debouncing
```

```

        if(--debounce_count != 0)
            return; // Not stable long enough
    delta = bits ^ optos; // Which bits changed
    if(delta) {
        int dir = 1;
        optos = bits; // New state
        if(delta & SHAFT_A) { // Was it A or B that changed
            while(delta & SHAFT_B) // If both not scanning fast enough
                ;
            dir = -dir;
        }
        if(bits & SHAFT_A) // Work out the direction
            dir = -dir;
        if(bits & SHAFT_B)
            dir = -dir;
        motor_pos += dir; // update position
    }
}

```

This keeps track of the shaft position: `motor_pos` increases as the filament advances. I then use a timer interrupt to decrement `motor_pos` at the rate I want the shaft to move at. `motor_pos` then becomes the error signal for my feed back loop. If it is positive the shaft is ahead of where it should be, if it is negative it is lagging. On-off control was too aggressive so I used PWM to give proportional control. Here is the code, called from the same fast interrupt :-

```

//
// Control the motor
//
#define MCYCLE 16
static void do_motor(void)
{
    static int mcount = 0;
    static int on_time = 0;

    if(mcount >= MCYCLE) { // At end of cycle?
        if(motor_pos <= 0) { // If lagging
            on_time = -motor_pos >> 3; // Set PWM for next cycle proportional to the lag
            mcount = 0;
        }
    }
    else
        ++mcount;

    if(motor_pos > 0 || mcount >= on_time)

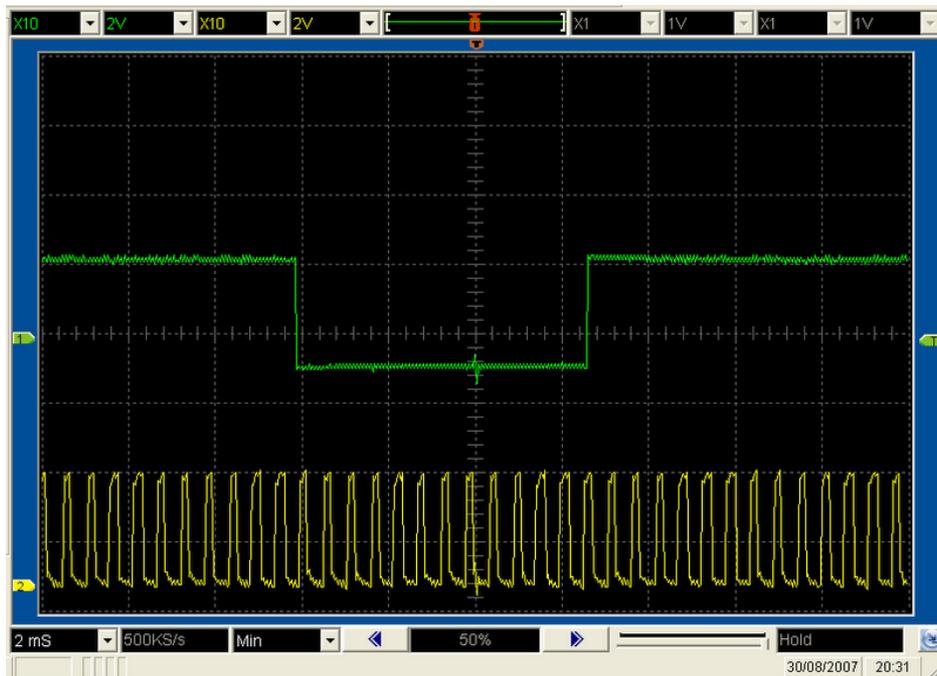
```

```

P2OUT &= ~MOTOR;           // Motor off
else
P2OUT |= MOTOR;           // Motor on
}

```

This is the resulting PWM waveform and one shaft encoder signal, my scope only has two channels! :-

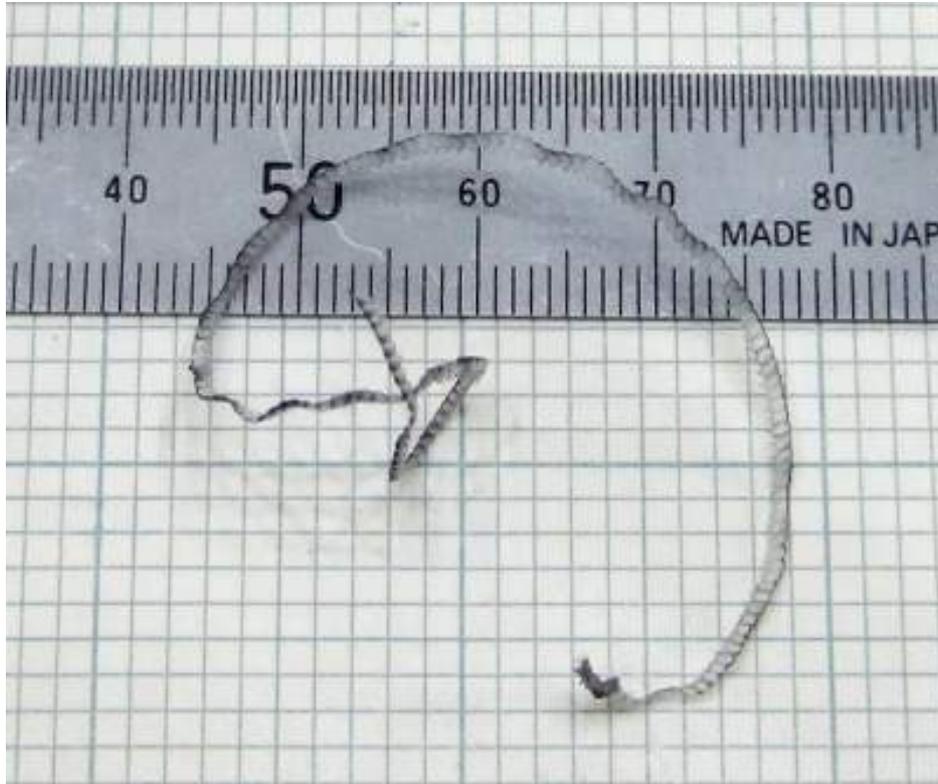


The speed control works well, no loss of torque as the speed is reduced. It has a bit of a damped oscillation with no load due to the slop in the gearbox but it is fine in the extruder where it has a constant load to hide the backlash.

# Caught in the act

Saturday, 1st September 2007 by Nophead

You may remember that I reported a ribbon of swarf coming out of the side of my extruder :-



It wasn't obvious to me how this was formed. When I stripped it down today I caught it in the act :-



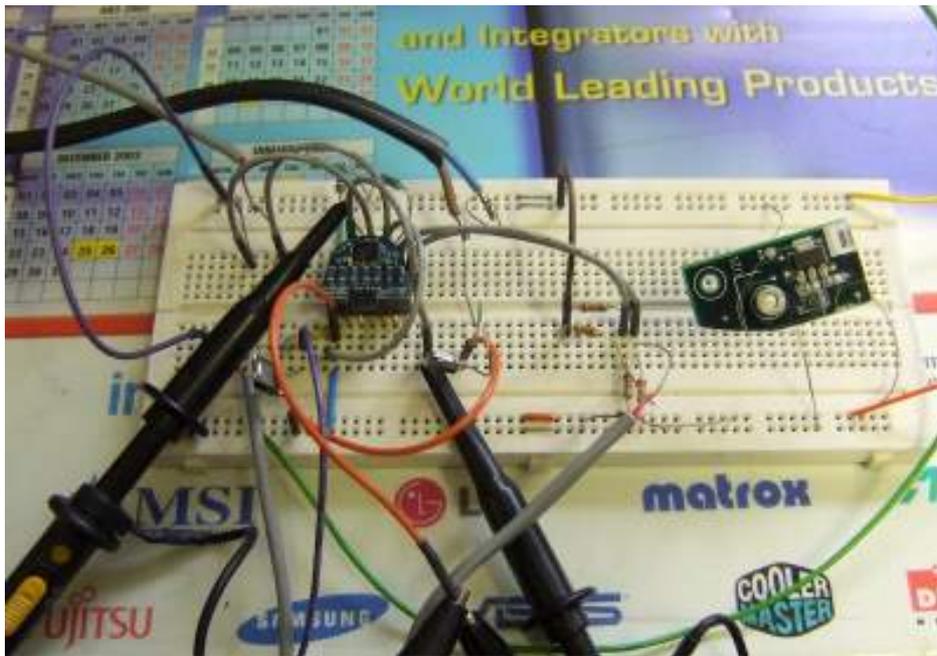
It appears that when the threaded rod cuts into the plastic it displaces a corrugated ribbon of material sideways. This remains attached to the filament at the leeward side and the ridges formed by the thread remain joined to each other by very thin webs. As it progresses down the pump it gets separated from the filament, presumably where it enters the barrel, and finds its way out through the side. I think the root cause is that when polymers like HDPE are stretched the long molecules get aligned length ways and it becomes very strong even though it is very thin.

# Getting nowhere fast

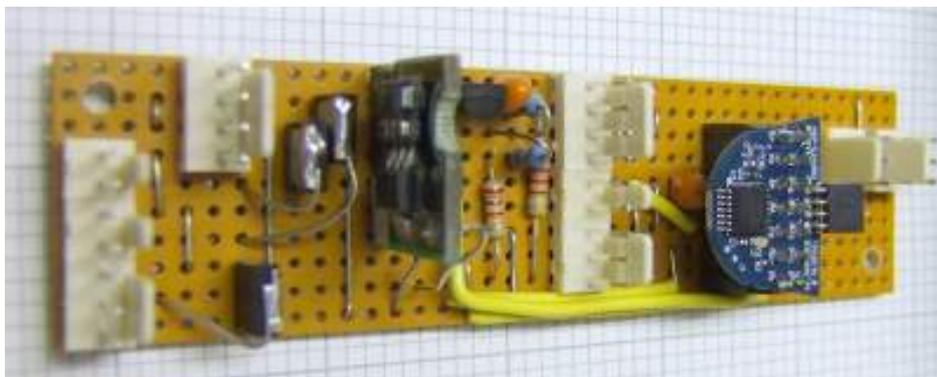
Thursday, 13th September 2007 by Nophead

Two weeks ago I had my extruder controller built on breadboard controlling the heater temperature and motor speed. All I had left to do was link it to my main controller and talk to it from my host software. This should have been easy as I already had I<sup>2</sup>C working to my spindle controller ...

The first thing that went wrong was the temperature reading from the thermistor started to become erratic. I decided this may be due to a bad connection as my breadboard layout was getting a bit messy.



The hot resistance of the thermistor is only about 12  $\Omega$  so I was willing to think a bad connection could be possible as I had not used the breadboard for over 10 years. I was also getting a lot of noise from the motor so I decided to rebuild the circuit on vero board and shorten all the connections.



I paid careful attention to the layout to keep the high power stuff away from the sensitive inputs

and the micro, and route the ground currents sensibly. The connectors on the far left are the outputs for the heater, motor and possibly a fan. Next is the power in connector followed by 3.3V and 5V regulators. The shaft encoder is 5V but the micro is 3.3V, the four resistors handle level shifting. Next are the input connectors for the shaft encoder, thermistor and filament exhausted sensor. The far connectors are for the I<sup>2</sup>C bus.

I mounted it on the z-axis together with my spindle controller so that the only moving wires are a 12V feed and the I<sup>2</sup>C bus.



All the wires are now much shorter and screened. I also earthed the casing of the motor. On testing I was very disappointed to find :-

1. The thermistor was still erratic.
2. The I<sup>2</sup>C bus did not work much at all.
3. The noise around the circuit was just as bad if not worse. Until I added the earth connection to the z-carriage the micro crashed when the motor was running.

Not the result I was hoping for!

# Toast

Friday, 14th September 2007 by Nophead

The first problem was easy enough to diagnose. Since I had rebuilt and rewired the circuit it had to be the thermistor itself. After removing it, I could see the underside was looking a bit toasted. I don't think it was designed for use up to 250°C. The insulation on the wire was not up to it and I suspect it was soldered to the actual device, and that the solder melted. There seems to be some solder on the brass nozzle now where it was mounted.

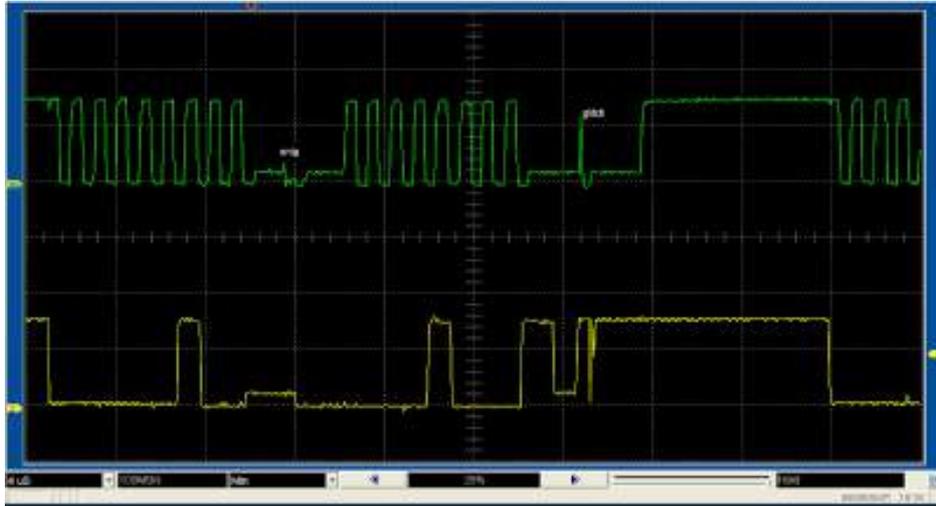


The remedy was easy: I just replaced it with the recommended glass bead thermistor which had arrived from back order in the meantime. It is rated to 300°C. Its characteristics are different so I had to change my resistor values, but I had anticipated that by mounting them on the connector rather than the board.

# Bus stops

Saturday, 15th September 2007 by Nophead

The I<sup>2</sup>C bus not working was more of a problem. I had some issues when I just had the spindle controller connected, see [bodge-it-and-move-on](#), but at that time I did not have a storage scope so I could not get to the bottom of it. In the meantime I bought a cheap 100 MHz 2 channel USB scope so I was able to find out what was going wrong.



As I have indicated above, the clock line has two glitches where it should have a proper clock pulse. The master generates the clock but the slave is allowed to stretch it by extending the low portion. Normally it is hard to tell which device is driving the bus but in this case it is obvious because I got the pull up resistors too small for the MSP430. I forgot that the MSP430 is aimed at low power applications so has an unusually low drive capability.

I still wasn't sure which end was the problem so I coded the host end in software so I could see exactly what the slave was doing. It is relatively easy to do an I<sup>2</sup>C master in software because it does not have any strict timing deadlines. The slave does, so it is more difficult to implement purely in software.

It turns out the problem lies with the mask revision of the MSP430F2013s that I am using. Revision B has several I<sup>2</sup>C bugs such as pulling the clock low when it shouldn't and no workarounds. I have had my chips for some time, long before I started this project. Two are actually labeled with a mask revision of X which is undocumented. It seems to have at least all the bugs in mask B. The other is labeled as mask B, so none are of any use for I<sup>2</sup>C!

Very disappointing that these days a device has to have three or four mask revisions just to get something as simple as an I<sup>2</sup>C module working. This seems to be the way things are going: hardware is becoming just as buggy as software. I wasted some time at work recently discovering that the UART in a PIC18F65J10 occasionally inserts zero bytes in the middle of your packet. These things were lab exercises when I was an undergraduate, now big companies can't get them right.

Fortunately, I had some MSP430F2012s that were mask revision B and the I<sup>2</sup>C bugs were fixed one revision earlier on that chip. They are slightly different in that they have a 10 bit SARADC instead of a 16 bit sigma-delta ADC. This is actually more appropriate for my application but it has a completely different software interface and voltage range.

Once I had swapped to the MSP430F2012 and modified the firmware for the new ADC, the I<sup>2</sup>C bus sprang into life. That was until I started to run the motor whereupon I got occasional bus lockups. This is due to the massive amount of noise coming from the brushes of the DC motor. I get about 2.5V of noise on the I<sup>2</sup>C lines

Using I<sup>2</sup>C without buffers for anything other than inter IC comms is a really bad design decision, I am not sure what came over me. I normally use RS485 differential comms when linking boards that drive motors or other high current loads and have never had a problem with noise. I even think I have publicly criticized the RepRap design for converting the RS232 to 5V signals before sending it around the ring of control boards. It was tempting to give I<sup>2</sup>C a try because I already had micros that support it, and didn't have UARTs, and my screened cable is only about a foot long. I<sup>2</sup>C is particularly susceptible to noise though because it is only actively driven low and because it is edge sensitive. Also the data rate I chose is five times faster than RepRap uses and I am using 3.3V logic rather than 5V. I<sup>2</sup>C also has the nasty feature that corruption can cause the bus to lock up which doesn't happen with asynchronous comms.

One thing I noticed was that earthing the can of the motor made things a lot worse by coupling the noise onto the ground rail. I established that the noise is conducted rather than radiated by running the motor from a separate bench PSU. I also managed to get it to run reliably by adding some 2200pF capacitors to the I<sup>2</sup>C lines, but that is a horrible bodge! Other things I will try :-

1. Change the pullup resistors from 1K to 2K2 so that the MSP430 can pull them fully low. That will increase the logic low noise immunity but make the logic high immunity worse.
2. See if I can program the master to clear the bus lockup.
3. Add a CRC and packet sequence flags so I can detect errors and do retries.
4. See if I can suppress the motor better.

If that doesn't fix it I may have to rethink the design. There are such things as high voltage I<sup>2</sup>C buffers but I expect they are SMT only. I could switch to differential comms or use a better DC motor, or replace it with a small stepper motor. That would also eliminate the need for a shaft encoder but I may struggle for torque.

# DC to daylight

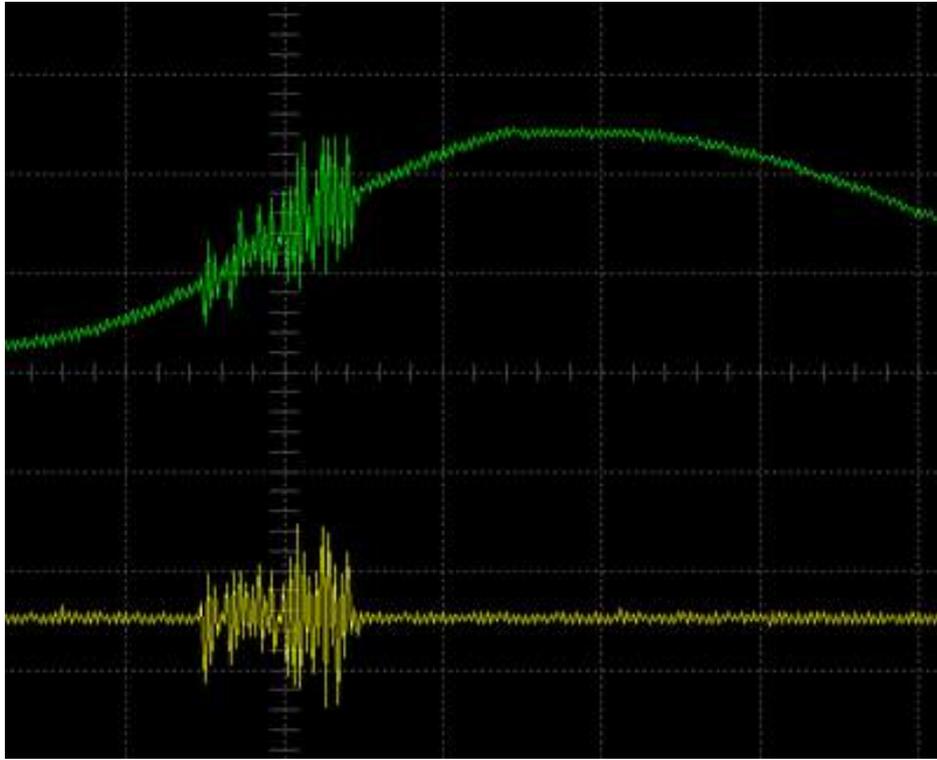
Tuesday, 18th September 2007 by Nophead

Well my machine is not going to pass any EMC regulations, my wife is complaining it is interfering with the digital TV downstairs! The amount of noise coming from the little GM3 gear motor is astonishing. This is the motor switching waveform on the top trace and the other lead of the motor which is at 12V on the bottom trace. The vertical scale is 20V and the timebase 0.4mS.



In this instance the motor is being powered for about 300  $\mu$ S every 1.3 mS when its negative lead is driven to ground. When the motor is switched off the voltage shoots up above 12V due to the back emf. It gets capped at 48V by the over voltage protection of the BTS134 low side switch that I am using to drive it. It then has a damped oscillation at about 6KHz before settling down to 12V for the remainder of the off period. This will be due to the inductance of the motor windings resonating with the 100nF capacitor I put across the motor terminals. Although it looks violent it is actually the smaller burst of noise on the right which is causing all the problems.

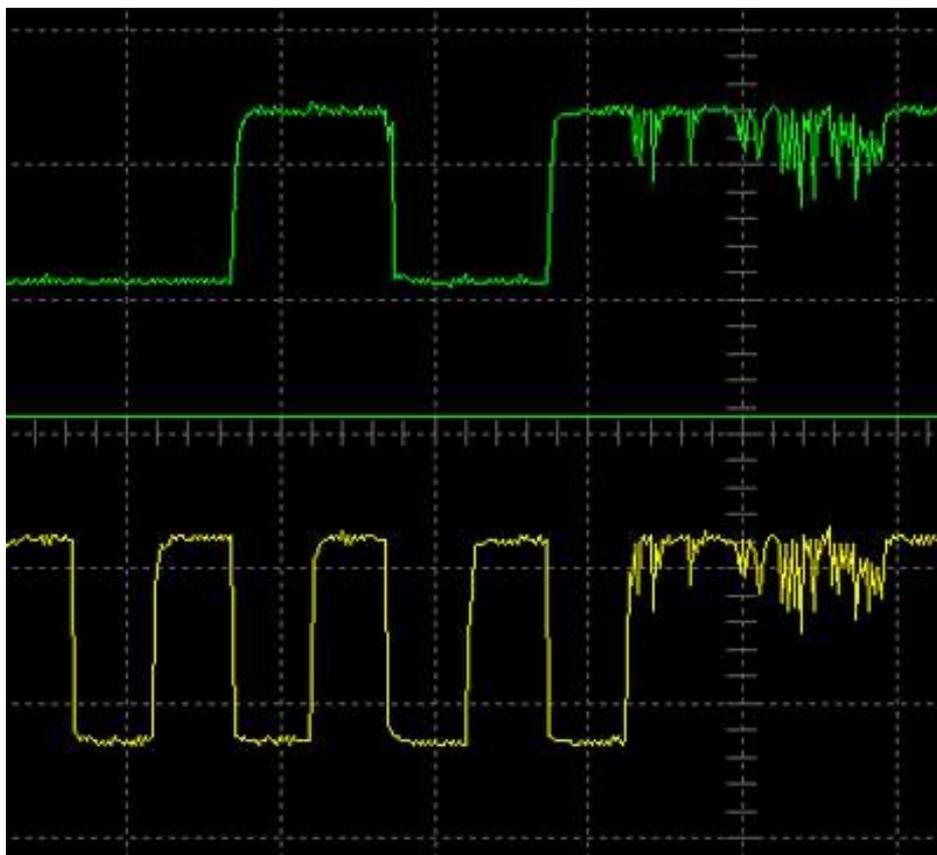
Here is a close up of a similar burst of noise with a timebase of 10 $\mu$ S.



This is around 20MHz and you can see it gets onto the 12V rail. It is caused by the sparks at the motor brushes. Sparks emit RF energy from DC to daylight as I was once told by an EMC expert. My guess is that 20MHz is the resonant frequency of the motor windings with their own stray capacitance when they are momentarily disconnected from my suppression capacitor by the commutator.

One nasty aspect of this sort of noise is that it tends to get less as the motor brushes wear in and then get worse again as they start to wear out. I remember a project where a small motor was mounted close to a PIC. The PIC would frequently crash when the device was first run, but it would soon become impossible to recreate the problem until a new motor was fitted. I read that it is a good idea to "break in" DC motors by running them without any load at a low voltage for a few hours to allow the brushes to become a good fit to the commutator. Too late for mine though!

This is what the noise that gets onto the I<sup>2</sup>C lines looks like :-



A tough challenge then to make I<sup>2</sup>C reliable in this environment!

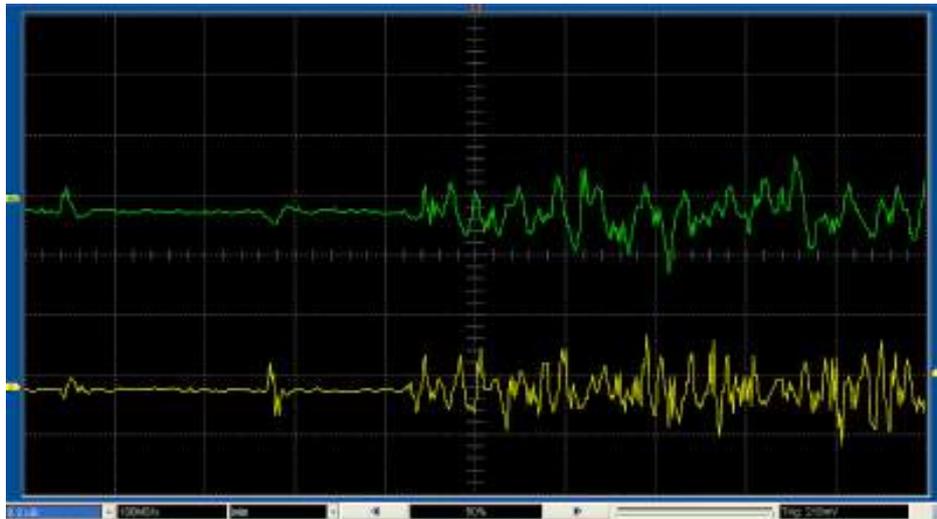
I began by stopping the comms from locking up so that I could add a retry scheme. To do that I had to put timeouts in all the points where I was waiting for the master controller to do something. When it times out I have to reset the controller and do one manual clock pulse to free up the slave before delaying 100uS and then re-enabling the controller. That stopped the comms locking up but did nothing to preserve data integrity. E.g., while I was sending motor commands and reading the temperature the heater came on of its own accord, not good!

The next thing I did was add an 8 bit CRC checksum to the end of each message so that I can detect when a message has been corrupted. 8 bits should be sufficient because the messages are only a few bytes long, i.e. less than  $2^8$  bits, and the bursts of noise are only a few bits long, i.e. less than 8. I used a table driven method so the software overhead is just a 256 byte table, one XOR and a table lookup.

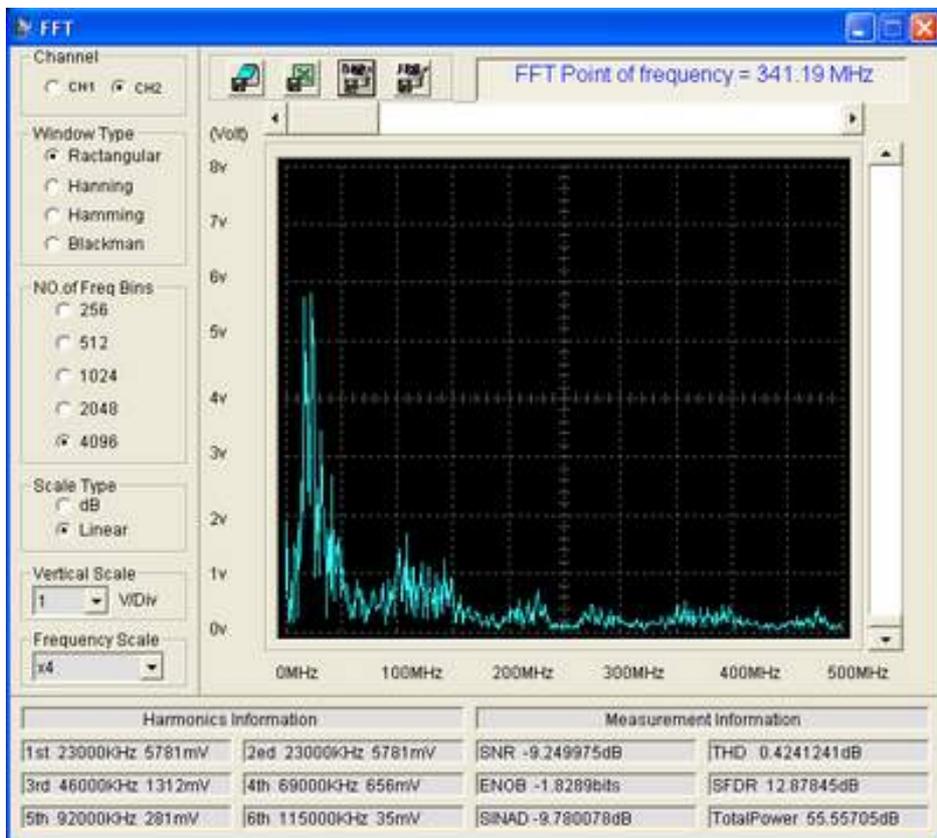
I also added a sequence flag to the top bit of the command byte. This alternates when a new command is sent but does not on a retry. This enables the slave to ignore retried commands resent by the master because the previous reply from the slave has been corrupted.

The result seems to be robust even with the massive amount of noise present but I don't like to paper over hardware problems with software. To make systems like this completely reliable I aim to get no retries in normal operation and only rely on the protocol to handle exceptional events. The root cause is the noise from the motor so I decided to have a go at tackling that.

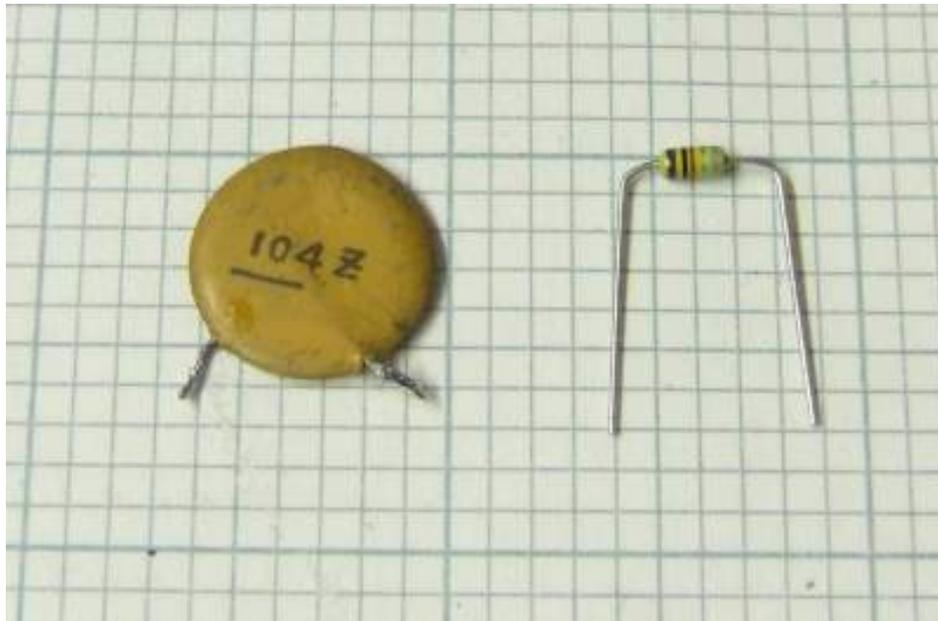
I took a closer look at the noise on the motor leads without any suppression :-



It looks pretty random and different on each wire which is to be expected because the two brushes spark independently. Here is a spectrum analysis :-

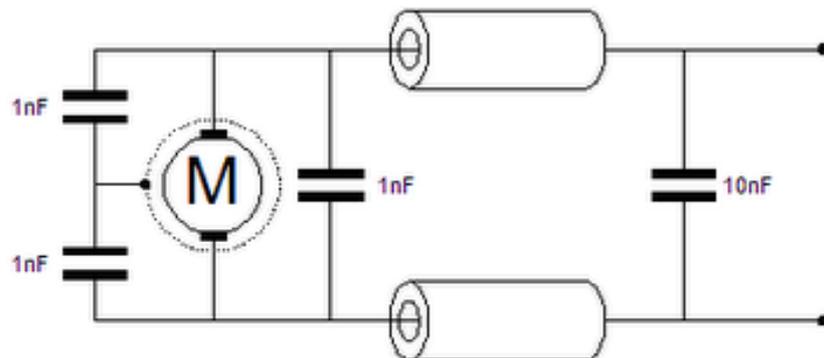


It peaks at 23 MHz but must in fact go all the way up to over 600 MHz to affect the television. There is also a lot of noise on the can. My first attempts to suppress it were to put a 100nF disc ceramic across the terminals and earth the can. That did not work well at all. I found that a more modern 1nF capacitor across the terminals worked better and leaving the can floating was better than grounding it because that just put noise on the ground rail. The old and new capacitors are shown below :-



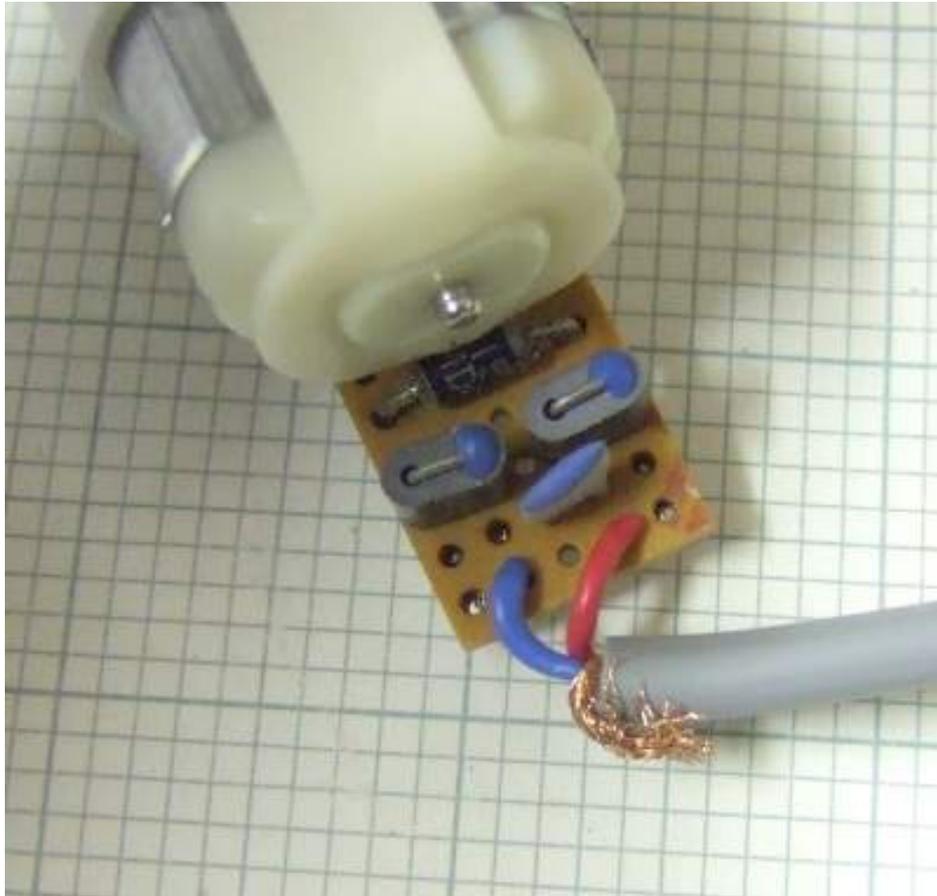
It is no surprise to me that the smaller one works better at higher frequencies because it is so much physically smaller its inductance will be less. It is also much kinder to the MOSFET driving it!

Doing a bit of research I found that it is common practice to connect a capacitor from each terminal to the can, so I added two more 1nF caps forming a triangle. That worked well as it got the retries on the I2C bus down to zero, and also stopped the TV interference. I could have stopped there but there was still plenty of noise visible on the scope. I added two small ferrite bead inductors that I salvaged from a very old disc drive, one in series with each lead, and put a small 10nF ceramic across the cable. That made a fantastic filter leaving no noise visible on the scope.

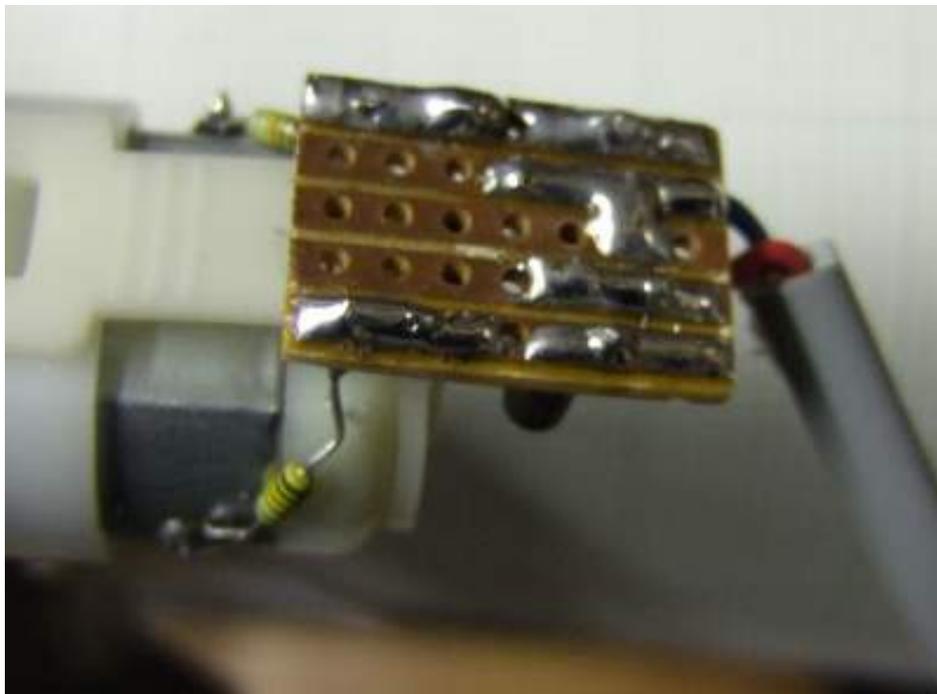


I also decided to add a back emf clamping diode rather than rely on the over voltage protection of the MOSFET. 48V across a 5V motor is a bit much after all and is high enough to give an electric shock.

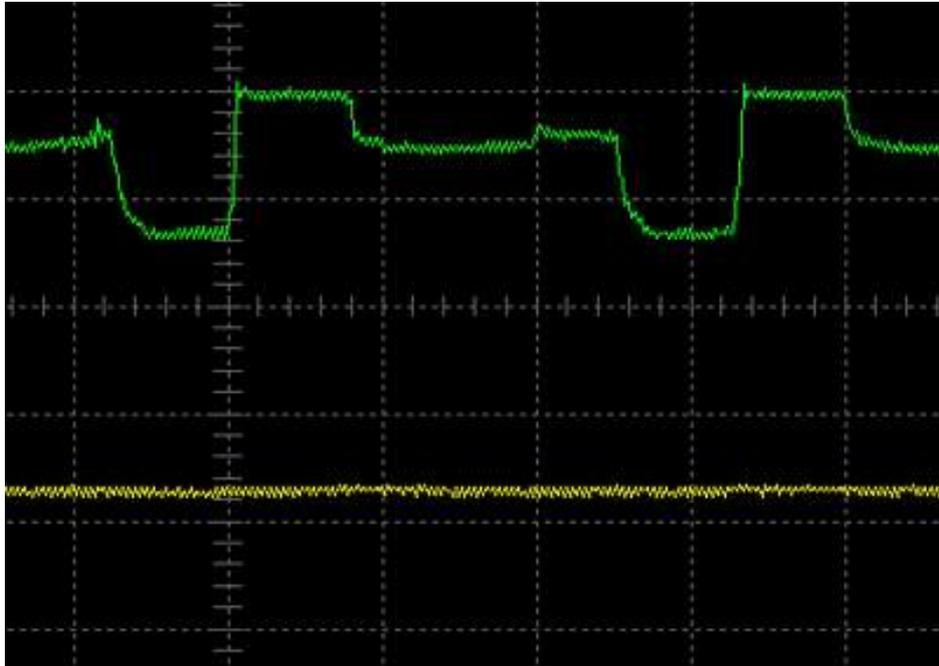
Here is the resulting filter mounted on Vero board and fitted to the motor :-



The 1nF cap across the motor is hidden by it and the other two are underneath :-



And here is the new switching waveform with pretty much all overshoot, ringing and noise eliminated :-



If only all EMC problems were that easy!

# Temperature drop

Saturday, 22nd September 2007 by Nophead

My extruder controller is working much better after I cured the motor noise problem. The 10 bit SAR ADC also seems to work better than the 16 bit sigma-delta version did. With the 16 bit one there was a lot of noise on the readings, even when the motor wasn't running. I had to average over many samples to get a consistent reading which delayed the response. With the 10 bit ADC I just read it and compare it with the temperature set point value to decide if the heater should be on or off. That gives a temperature swing of about  $\pm 3^{\circ}\text{C}$  with the heater going on and off every four or five seconds.

The temperature is calculated from the ADC reading and vice versa by the PC with the following Python class :-

```
from math import *

class Thermistor:
    "Class to do the thermistor maths"
    def __init__(self, r0, t0, beta, r1, r2):
        self.r0 = r0 # stated resistance
        self.t0 = t0 + 273.15 # temperature at stated resistance, e.g. 25C
        self.beta = beta # stated beta
        self.vref = 1.5 * 1.357 / 1.345 # ADC reference, corrected
        self.vcc = 3.3 # supply voltage to potential divider
        self.vs = r1 * self.vcc / (r1 + r2) # effective bias voltage
        self.rs = r1 * r2 / (r1 + r2) # effective bias impedance
        self.k = r0 * exp(-beta / self.t0) # constant part of calculation

    def temp(self,adc):
        "Convert ADC reading into a temperature in Celsius"
        v = adc * self.vref / 1024 # convert the ADC value to a voltage
        r = self.rs * v / (self.vs - v) # resistance of thermistor
        return (self.beta / log(r / self.k)) - 273.15 # temperature

    def setting(self, t):
        "Convert a temperature into a ADC value"
        r = self.r0 * exp(self.beta * (1 / (t + 273.15) - 1 / self.t0)) # resistance of the
thermistor
        v = self.vs * r / (self.rs + r) # the voltage at the potential divider
        return round(v / self.vref * 1024) # the ADC reading
```

It is instantiated as follows :-

```
thermistor = Thermistor(10380, 21, 3450, 1790, 2187)
```

10380 is the resistance of the thermistor measured by my multimeter at a room temperature of 21°C. 3450 is the beta of the thermistor taken from the data sheet. The last two values are the two resistors forming a potential divider with the thermistor wired across the second one, again the values are measured with a multimeter. The fudge factor of  $1.357 / 1.345$  corrects the MSP430 internal reference voltage so that it agrees with the multimeter.

The result seems to track the temperature measured by a thermocouple to within about 5°C, good enough for me. Just as I had finished checking it, I knocked the thermistor leads with my thermocouple and it fell off. It was stuck to the brass nozzle with JB Weld but I forgot to roughen the surface first. I am now waiting 16 hours for it to set again.

The extruder controller firmware is only about 400 lines of C. As well as temperature control it also controls the DC motor precisely using the shaft encoder and handles the I<sup>2</sup>C protocol.

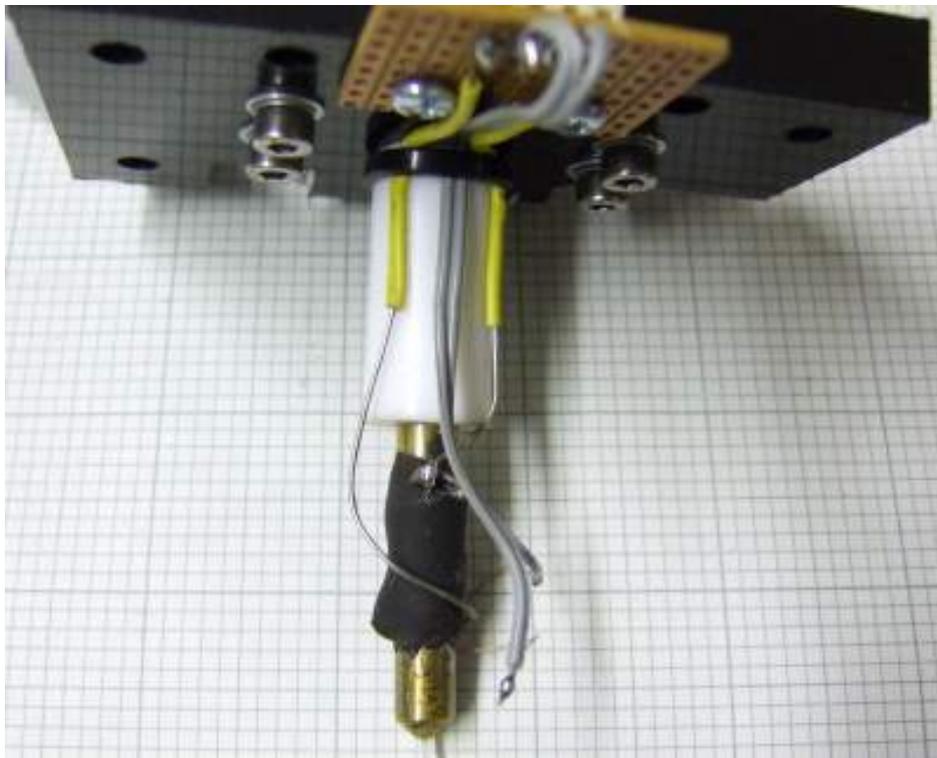
I have now completed all the mechanical parts, the electronics and the firmware. I just need to get the RepRap host code to talk to my non standard hardware to complete the machine.

# Self destruction

Monday, 24th September 2007 by Nophead

Not managed any self replication yet but my machine has done a bit of self destruction!

While doing some experiments running my extruder at different speeds and temperatures, I managed to run it at too low a temperature such that it forced the PTFE barrel out of its clamp. That broke off one of the heater wires under the JB Weld. Fortunately I was able to dig out the end of the nichrome and reconnect it. I soldered the joint but that is not the best idea as solder melts at 183°C and I am running my barrel at about 200°C. The heater gets a bit hotter than that. Presumably molten solder is still a good conductor. The ideal way to make the connection would be with a miniature barrel crimp but I don't know if they exist. Here it is repaired :-



Clamping a very slippery plastic rod with a clamp made out of a slightly less slippery plastic is probably not the best design.

I seem to spend as much time stripping down and rebuilding my extruder as I do running it. Looking on the bright side at least the thermistor didn't fall off again despite some rough treatment. Here it is all back together again and working :-



# Equations of Extrusion

Friday, 28th September 2007 by Nophead

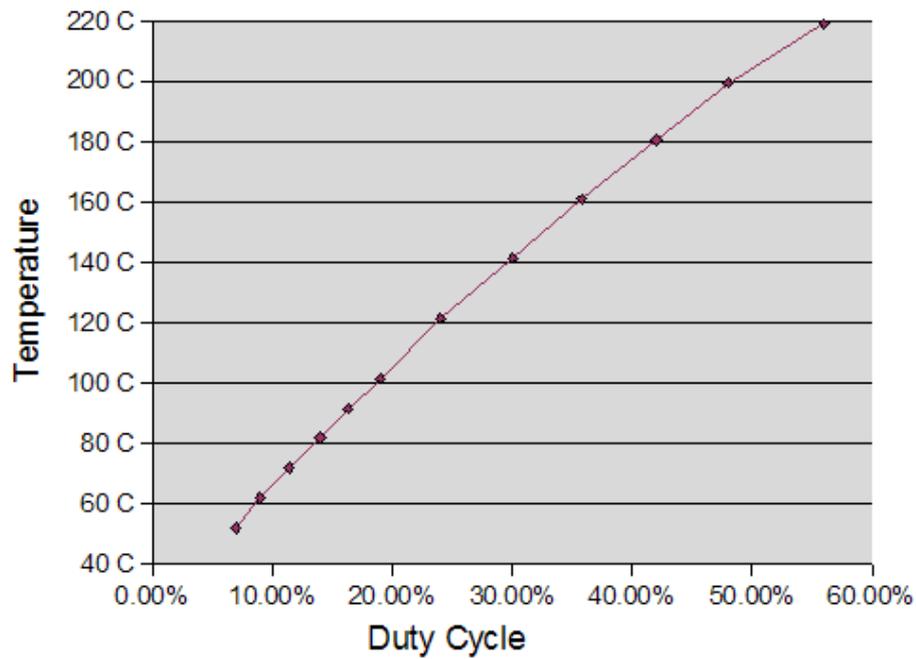
When I first tested my extruder I found that the filament diameter varied with the flow rate and temperature. This was contrary to what others have experienced so I decided to investigate further. It turns out that this is known as die swell and is caused by non Newtonian fluids expanding after they have been squeezed through a hole. Apparently it is a very complicated subject.

To get an idea of what was going on I designed my extruder controller to be able to make measurements. Rather than drive the motor with open loop PWM I used a shaft encoder with proportional feedback. Instead of specifying what PWM setting to use, the host specifies how many shaft encoder steps to move and at what rate. The extruder controller then adjusts the PWM to maintain the correct shaft position at any given instant. Assuming the filament does not slip against the drive screw, that means I can extrude a known volume of plastic in a known time to the tolerance of the the original feed material. The host can then ask the controller what the total on time and off times have been so that it can calculate the average power that has been used.

My temperature control works in a similar way. The host calculates the resistance the thermistor should have at the desired temperature, and from that, what voltage reading the ADC should produce. It sends that setting to the controller which turns the heater on and off. Again it keeps track of the total on and off times so that the host can calculate the average power.

My heater has a resistance of 8.5  $\Omega$  and has 11.8V across it after the drop in the MOSFET switch and the wiring. That gives a power of 16.4W. This is a graph of the temperature reading from the thermistor plotted against the heater duty cycle :-

## Temperature v Duty Cycle

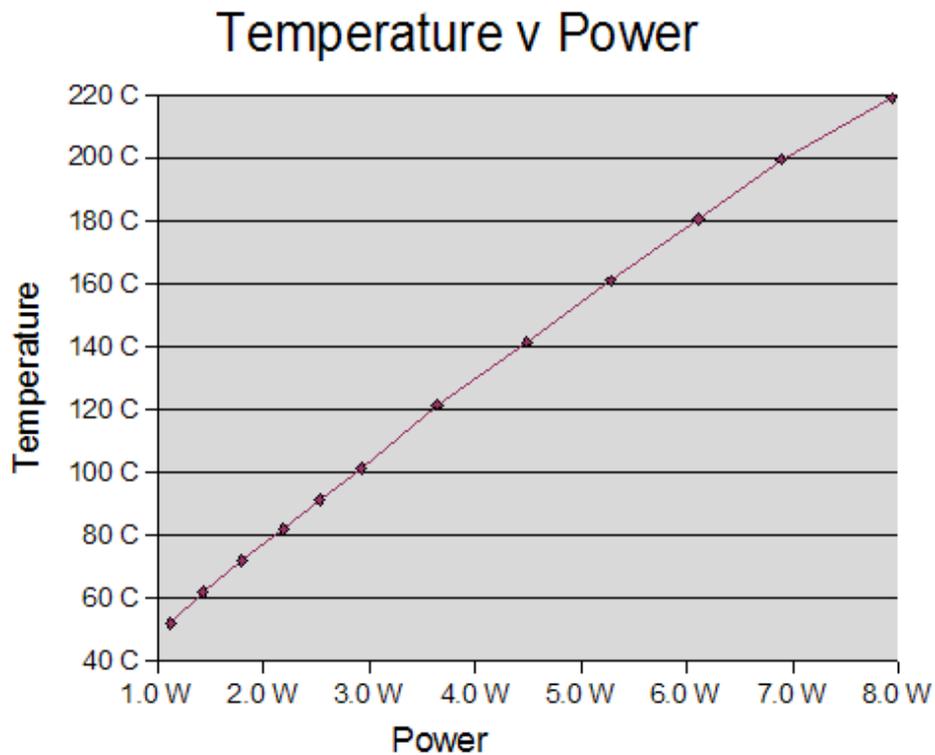


As you can see it is not quite a straight line. This is because the resistance of the nichrome heating element increases slightly as it gets hotter, so power does not quite rise in line with the duty cycle. I measured the resistance at 200°C to be 9.7 Ω. Using the formula:

$$R = R_0[1 + \alpha(T - T_0)]$$

that gives a temperature coefficient  $\alpha$  of  $7.8 \times 10^{-4}$  which is about twice the figure I found on the web for nichrome. I expect that it varies widely according to the exact alloy being used.

Here is a graph of temperature against power, calculated using the above formula for resistance :-

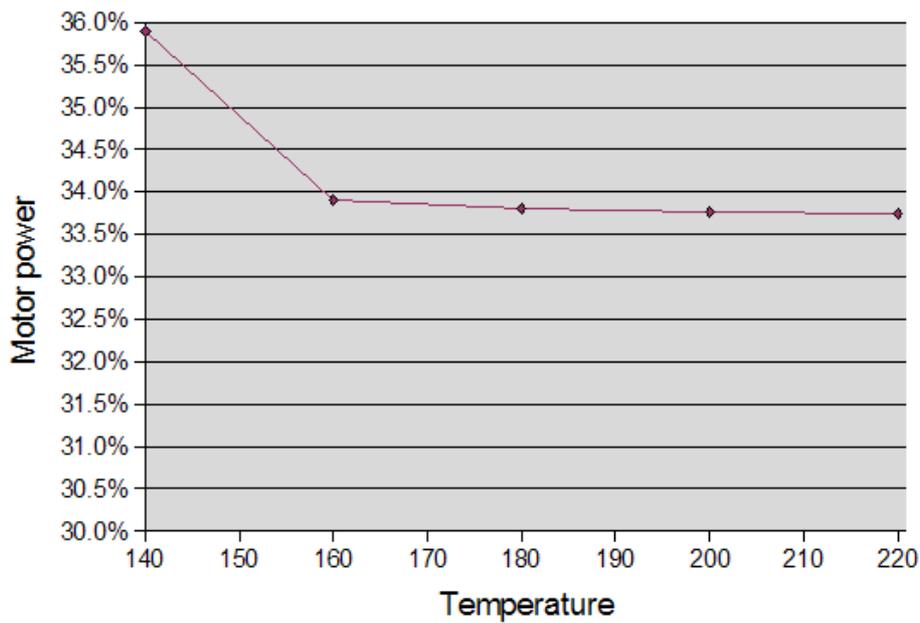


It is a lot closer to the straight line I was expecting.

I decided to investigate how much extra power is needed to heat the incoming plastic when extruding. I found that while feeding the filament in at 1mm/s, which is about the maximum my motor can do, the PWM to maintain 200°C increased from 44.6% to 61.2%. An increase of 16.6% corresponding to an extra 2.4W. Feeding a 3mm filament at 1mm/s gives a flow rate of  $7.1 \cdot 10^{-3}$  cc/s. HDPE has a density of around 1 so that is  $7 \cdot 10^{-3}$  g/s. The specific heat capacity is 2.2 J/g-°C which gives 2.8W to heat 7 mg from 20°C to 200°C per second. I think that is reasonably close to the value I measured, given that HDPE has quite a wide range of densities.

Next I decided to look at the effect of temperature on the motor power required to extrude at a given rate :-

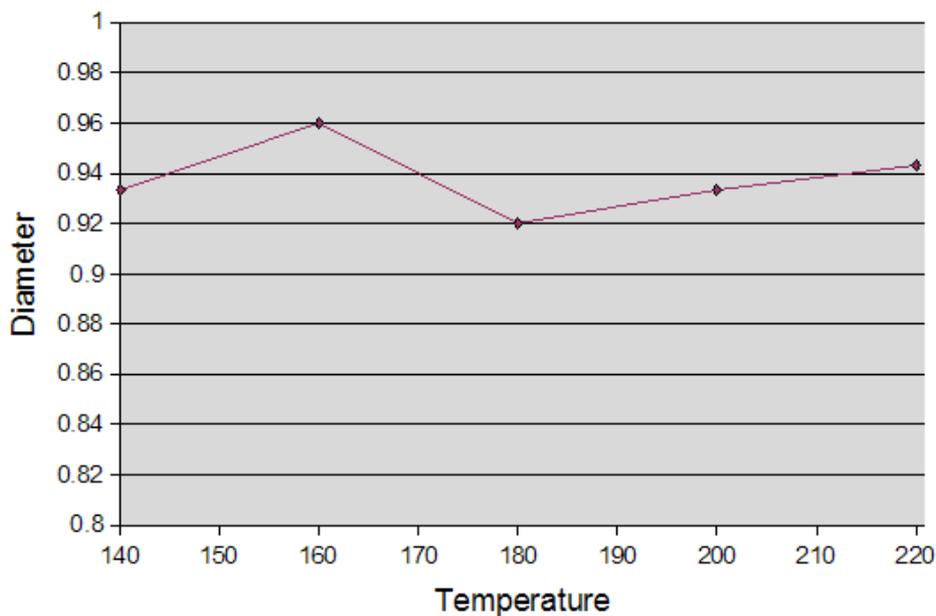
## Motor power v temperature



I concluded that temperature has little effect on the motor power required, except when it gets close to the melting point, where it rises rapidly as expected. That was how I broke my extruder!

Next I looked at filament diameter against temperature :-

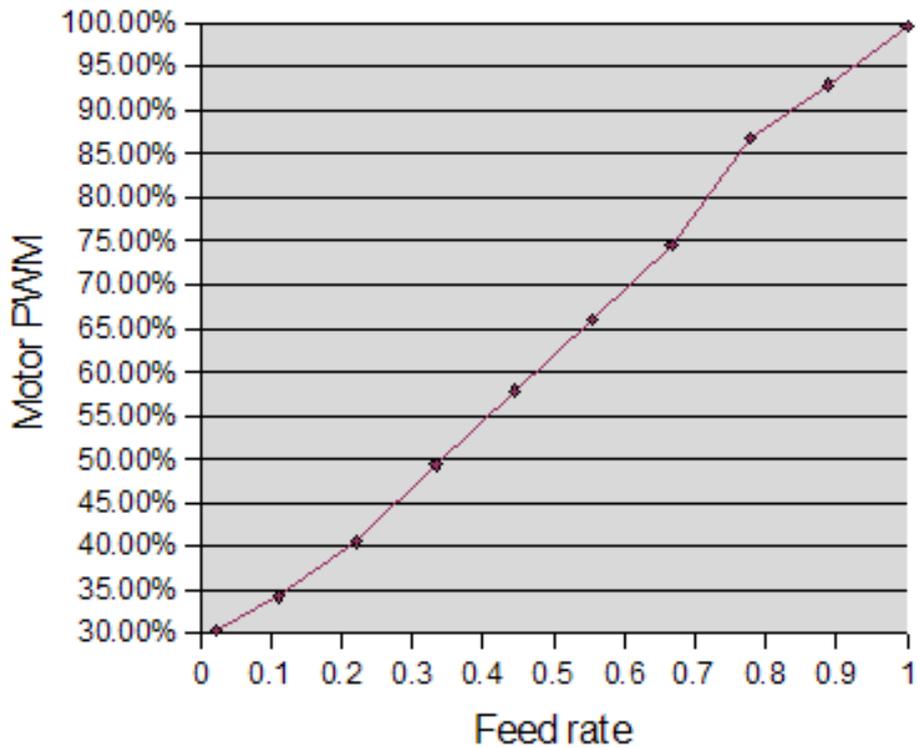
## Filament diameter v temperature



No real correlation, so it seems temperature is not very important as long as it is above the melting point. This was a surprise to me as I imagined molten plastic would get less viscous as temperature increased. It may become more critical when I start laying down filament as it will effect how it fuses together and shrinks. I did all the subsequent measurements at 200°C.

Feed rate (in mm/s) against PWM was another surprise. I expected power to rise rapidly with feed rate but, in fact, it is quite proportional :-

## PWM v feed rate



Presumable 30% is the power required to overcome static friction in the system.

Here you can see the output rate versus the feed rate :-

## Output rate v input rate

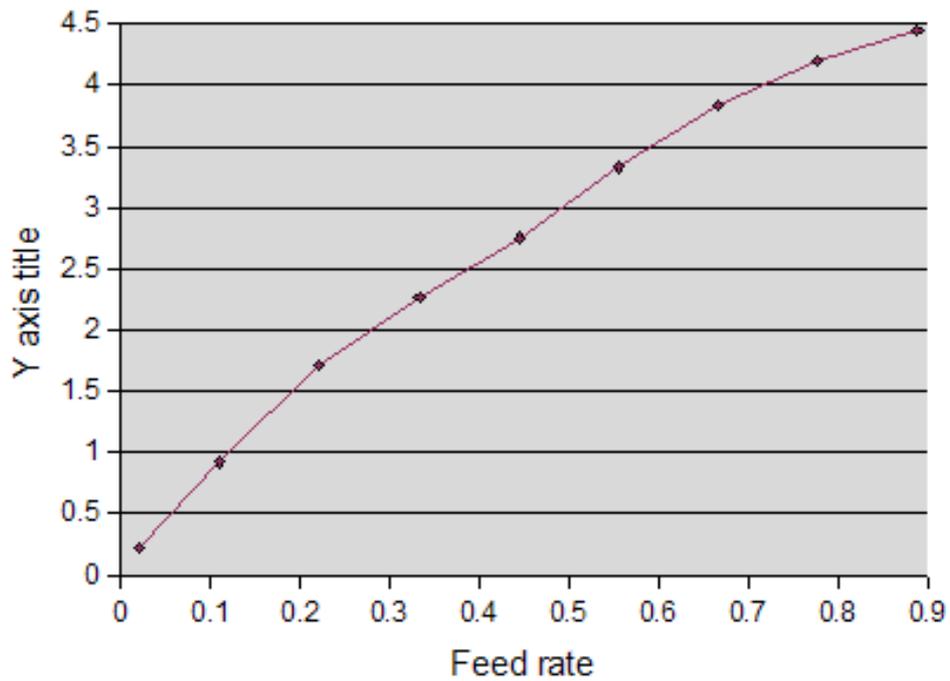




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It does not increase in proportion, so if conservation of matter is true then it must be getting bigger in diameter. Indeed it does, here is output diameter against output rate :-

### Filament diameter v output rate

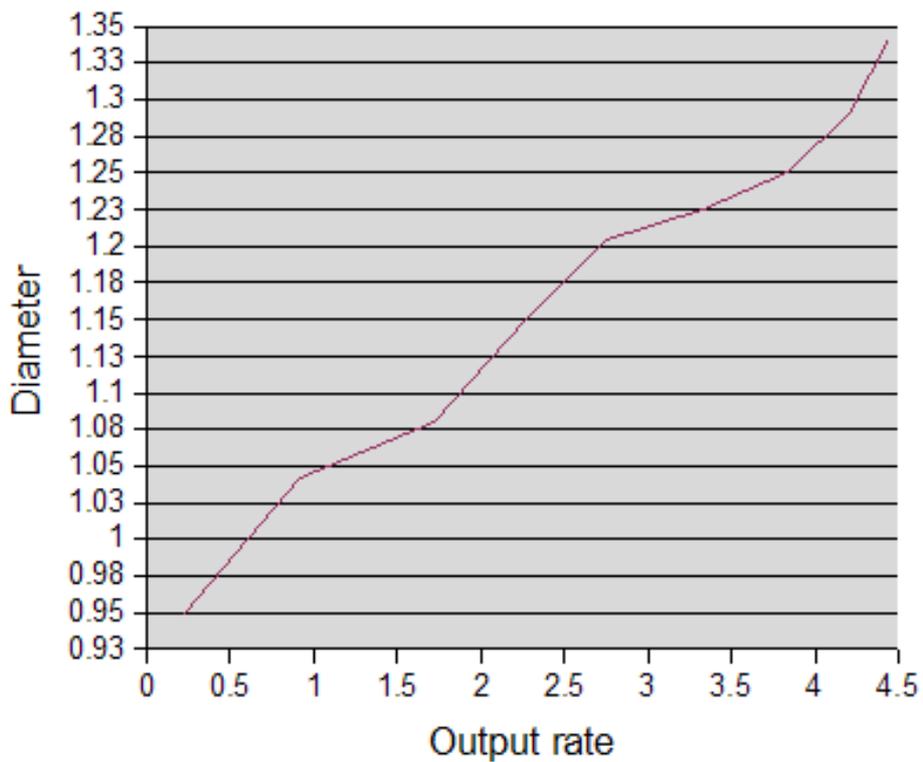


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Either it is a very complex relationship with multiple inflexions or it is just linear with lots of measurement error. I made three measurements per test with digital calipers and took the average but the deviation between samples was quite high.

I prefer to think it is a simple linear relationship which means I can make a simple mathematical model of my extruder. As you can see it will hit the Y axis at about 0.93 mm. I think that must be the size of the hole in my nozzle. I drilled it 0.5mm but perhaps I drilled the hole from the back too far and opened it out a bit. It seems to have got bigger with use because I could get 0.8mm filament when I first tested it but I don't seem to be able to now, even at very low extrusion rates.

So if the filament diameter equals hole size plus a constant times extrusion rate then from conservation of volume I can relate the output rate to the feed rate.

$$d_o = d_h + kv_o$$

$$v_o d_o^2 = v_i d_i^2$$

So:  $v_o(d_h + kv_o)^2 = v_i d_i^2$  a cubic equation!

Where  $d_o$  is the output filament diameter,  $d_i$  is the input filament diameter,  $d_h$  is the nozzle hole diameter and  $v_o$  is the output filament speed,  $v_i$  is the input filament speed.

With these equations I can calculate the output rate to get a particular filament diameter. That also tells me how fast to move the head. From the output rate I can also calculate the feed rate required.

Conclusion? Well I definitely have die swell which increases with extrusion rate but other people have reported constant die swell. The only explanation I can think of is that I drilled my nozzle too deep from the back so the aperture has almost zero thickness instead of the 0.5 to 1mm expected.

I have a simple mathematical model which allows me to exploit the variable filament width if I need to. This may all become irrelevant when I start laying down filament to build things because the filament can be stretched or compressed if the head movement does not match the output rate.

Tomorrow I will try laying down the filament.

# Dribble and smoke

Sunday, 30th September 2007 by Nophead

Not a very good day today. I started by trying to lay down a 50mm straight line of HDPE. I completely failed and ended up smoking my machine!

The first problem I decided to tackle was extruding just the right amount of filament. This should be easy because I can instruct my extruder controller to turn the pump an exact amount. Using the equations I described last time, I know what feed rate is required to give a particular diameter filament and what its exit speed will be. The problem is that when the extruder stops, the filament continues to extrude slowly for a while afterwards. This is because the molten plastic, being non Newtonian, is compressible.

To start with I was getting about 12mm of overrun. I have noticed that the flexible drive made from steel wire gets wound up and stores some energy. With no power applied to the motor it actually unwinds a bit driving the motor backwards. By default my software was preventing that because it monitors the shaft position and applies increasing power as the shaft moves backwards until equilibrium is reached.

The host can instruct the controller to turn off the motor completely and let the wire unwind. That reduces the overrun to about 4mm. The shaft encoder sees the motor go backwards so, when it's told to move again, it regains all the backlash as fast as it can before settling down to the desired speed. Therefore, there is no cumulative loss of accuracy in letting the wire unwind and wind up again.

I expect the amount of filament overrun could be reduced further, or even eliminated completely by running the pump backwards a bit at the end. Unfortunately I can't do that because this is what happens to the steel wire when it is turned the wrong way:-

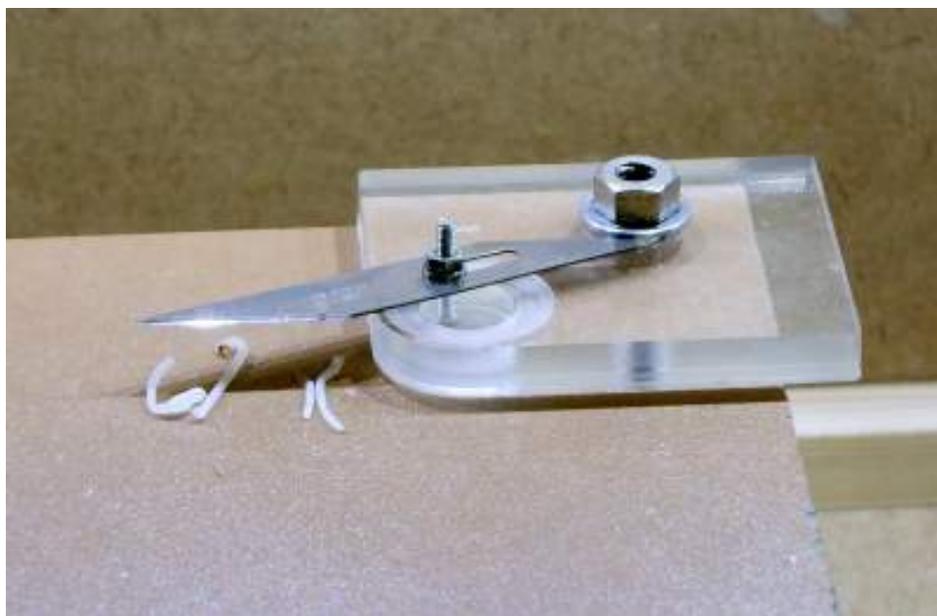


Because of this I designed my electronics to only be able to go forwards. Apparently this effect is not observed on the RepRap at Bath university. They are using 3mm wire, whereas mine is only

2.5mm, so that might account for it. I may see if I can get better wire that won't unwind. If so I will have to upgrade my drive to an H-bridge to allow the motor to be reversed. There isn't any spare room on my Vero board so I will either have to make a new one or make some sort of 3D creation.

In the meantime I decided to bodge round the problem. As well as the 4mm overrun when the motor stops, it also extrudes about 15mm when the heater is allowed to cool down and is then warmed up again. This is usually accompanied by a sharp cracking sound which sounds like trapped air bursting through the HDPE. I am not sure of the exact mechanism, but air must get in when the plastic is cold and contracted and then get trapped while it is heating up again, forcing some molten plastic out. Perhaps I have discovered a new type of pump with no moving parts!

So, before I can start extruding I need to remove the excess filament hanging from the nozzle. I did this by attaching a scalpel blade to one corner of my XY-table and having the machine visit it to wipe its nose just before starting to extrude. It is just a lash up at the moment, it would be better if it was 20mm above the table and a razor blade might be better, but it seems to work OK.



Of course, once the overrun has occurred and been removed, there is a net deficit of material which manifests itself as a delay before extrusion starts when the motor is switched on again. That has to be made up by starting the extruder in advance of moving the table for the first line segment.

So the next step was to lay down the filament on the table in a straight line. The first problem was that I discovered a bug in my software that meant the table only moved at half the specified rate. So any previous references to milling feed rates in this blog need to be halved!

The bug was easily fixed of course but I could not get the filament to stick to my table. When it hits the table it curls upwards into a loop and sticks to the side of the hot nozzle. The table surface I used for milling is made of upside down laminate flooring. It is covered with a textured layer of what I assume is probably some sort of vinyl. No great surprise it didn't stick, the next thing I tried was paper, a post-it note to be precise. That did not work either so the next thing to try was MDF.

I taped an 18mm block to the the table for a quick test and raised the z position by 18mm, but I forgot to program it to raise up to clear it after visiting the knife. The result was the nozzle collided with the block and that pushed the thermistor wires so they touched the heater wires.

The result was quite spectacular, the thermistor wires, being quite thin, lit up like a light bulb before burning out. The thermistor is toast and so is the micro. Three volt micros don't like 12V up 'em!

I should have insulated the wires but I didn't have any insulation handy that would stand the temperature. Also three 3A diodes in series across the thermistor would have saved the day but it's a bit late now.

Fortunately I have a couple more micros and a spare thermistor but the machine will be out of action for 24 hours while the JB-Weld cures.

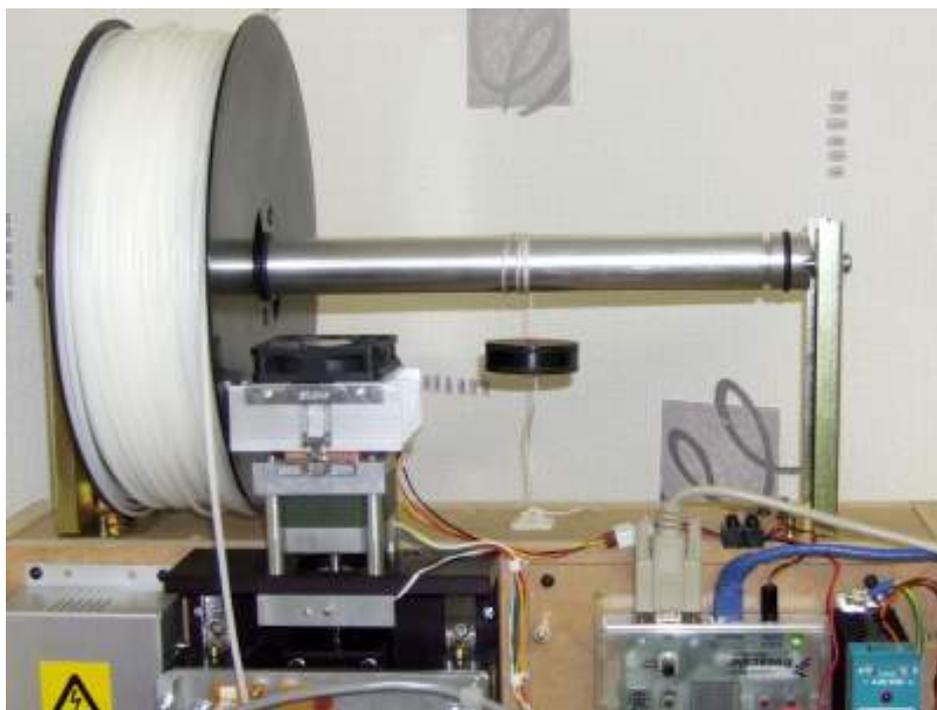
It is very easy to get a tool crash with a 3D machine and it usually causes a lot of damage. When I was using it as a milling machine I got into the habit of getting it to mime what it was going to do by running the program with a Z offset higher than the workpiece. I should have done the same thing this time.

# Taking up the slack

Sunday, 7th October 2007 by Nophead

I had a problem with my HDPE filament getting unwound from its reel. Because my extruder is attached to the z-axis, the filament gets pulled off the reel as the z-axis descends, but when it rises back to the home position there was nothing to take up the slack. Also the springiness of the HDPE makes it want to unwind. It needs a constant back tension to take up the slack and keep the filament on the reel.

My first idea was to attach a small DC motor to the roller to provide a backwards pull. As the motor would be permanently stalled I would have had to limit the current to something reasonable. After some thought I came up with a much simpler solution. I wound some picture cord around the roller and hung a weight from it. As the filament unwinds it lifts the weight. The weight is also tethered to the top of the machine, so once it gets to the maximum height it stops. The reel is only a friction fit on the roller so it starts to slip at that point. When the axis ascends again the weight falls and winds the reel backwards, taking up the slack. There is enough travel on the weight to cover the full z-axis travel, even when the filament has been used down to the inner diameter of the reel.



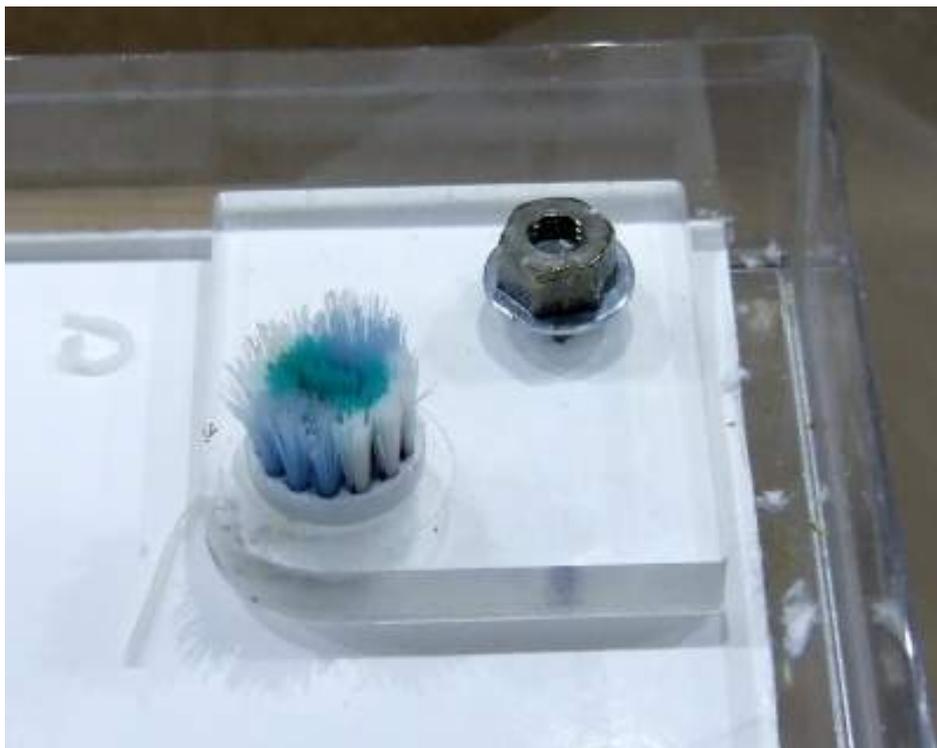
# Brush off

Sunday, 7th October 2007 by Nophead

HydraRaptor was using a knife to remove excess filament from the extruder :-



It always cut the filament OK, but it was random whether the loose bit fell off or stuck to the far side of the nozzle. The soundtrack of a video I saw of a commercial FDM machine said that they use a brush. I thought I would need a wire brush for 200°C but then I reasoned that, if the nozzle passed through fast enough, the high specific heat capacity of plastic might mean that it would not have time to melt. I decide to give it a try with an old electric toothbrush head :-



It does seem to work quite well. Here is a video of it in action :-

The scrap of filament sometimes stays stuck to the brush but subsequent passes eventually knock it off.

When I was using HydraRaptor for milling I had a tray around the table and a plastic skirt to protect the mechanism of the precious XY table from loose plastic chips. When I moved on to FDM I thought these would not be needed because it is a lot less messy. Actually I was wrong as HDPE chips are appearing, presumably from inside the extruder, and the filament offcuts sometimes ping off from the brush. I have therefore refitted the tray and skirt.

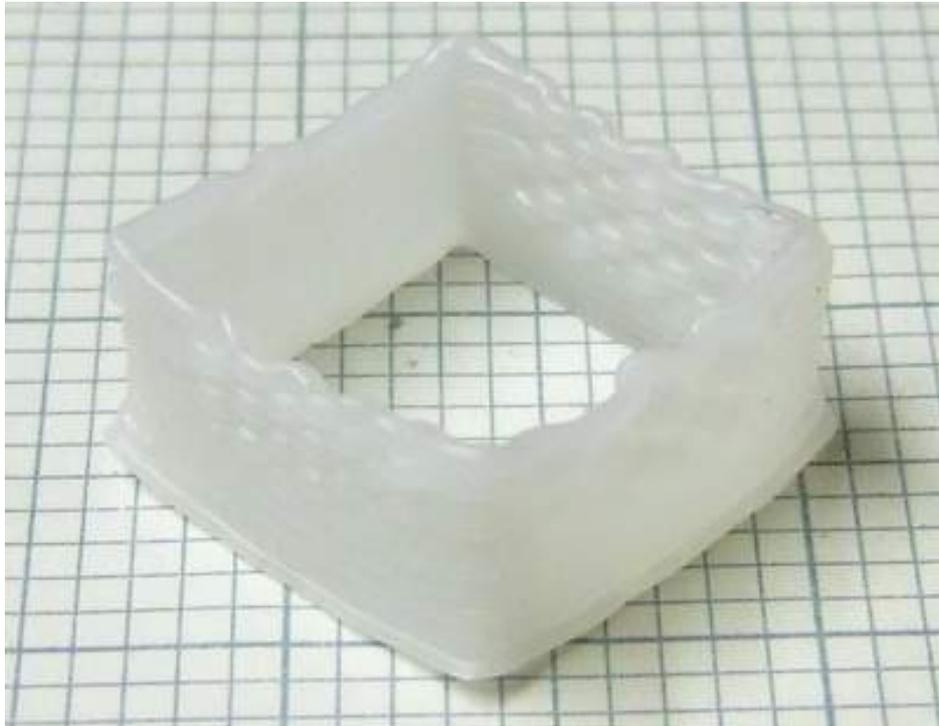
# Laying it on the line

Monday, 8th October 2007 by Nophead

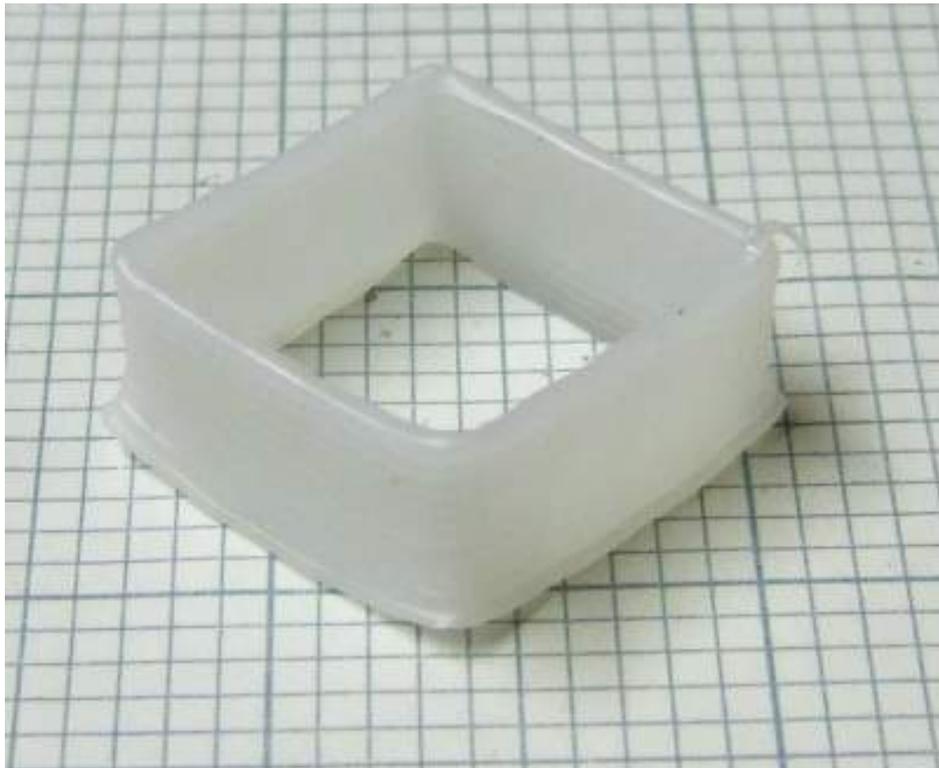
I decided to investigate the conditions necessary for multiple layers of HDPE filament to stick together so I wrote a little Python test script to extrude 20mm squares stacked on top of each other. From my graphs in [equations-of-extrusion](#) I chose an output rate of 3mm/s which gives a filament diameter of about 1.2mm. That only requires about 60% PWM which I thought was not too stressful for a 5V motor running from 12V. I set the heater temperature to 200°C. Here is the first run :-



The first two layers look reasonable and then we are into basket work! The z-axis was raising 1.2mm between each layer but, although the nominal filament diameter should be about 1.2mm, the sides were not growing at the same rate. That meant the filament was dangling allowing it to wiggle around. Next I reduced the z-increment to 1.1mm :-

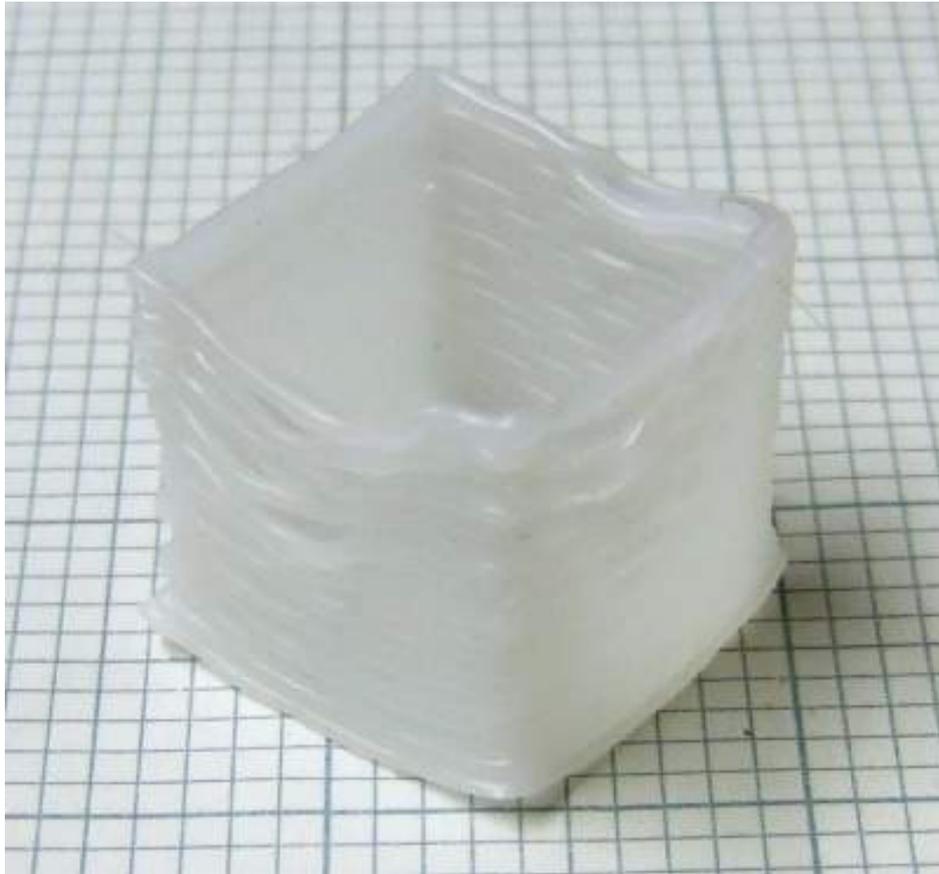


Better, the first four layers are OK this time, so obviously I tried z-increment 1.0mm next :-



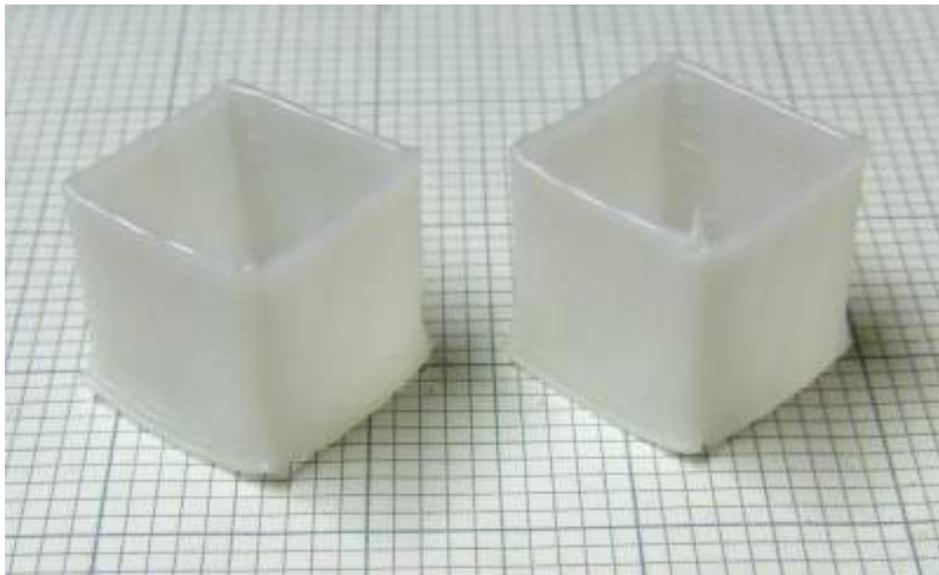
Much better! What is happening is that the filament is no longer cylindrical. Each layer is about 1.0mm high and 1.4mm wide. It could be due to gravity but I think it is more to do with being bent through 90° as it comes out the end of the nozzle.

The fact that the filament weaved about when the nozzle was too high made me think that the feed rate might be too fast so I did a taller test with the XY travel 20% faster :-



Another basket case! What is happening here is that there is not enough material so the filament slumps down and holes start appearing.

I went back to the original feed rate and did a couple of 20mm high tests to check consistency :-



These are actually incredibly strong in the vertical direction. I can stand on one and it takes my full weight. Here is a video of the one on the right being made, the middle section is sped up 8 times :-

I also ran a test at 160°C to see if the filament would still weld to the layer below. It did but it did not stick to the foam board.

As you can see the main defect is that the bottom corners curl up. This was completely expected from the work Forrest published here: [Ten-layers-with-no-curling](#), so next I will try his solution of laying down a raft first.

Another defect is that the filament width varies in waves. These seem to be related to the rotation of the extruder drive screw. You can hear the motor labouring more on part of the revolution. I think it is because something in the drive is a bit eccentric but more investigation is required.

# Measuring temperature the easy way

Tuesday, 9th October 2007 by Nophead

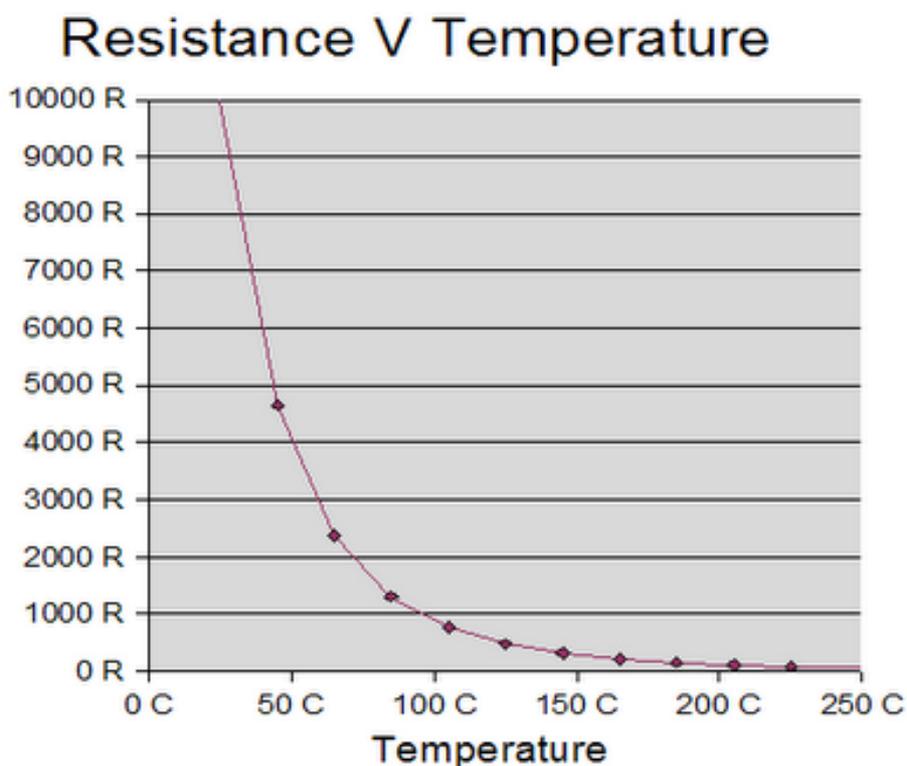
I have been asked for more details on my temperature measurement scheme so I have consolidated some of my previous articles :-

The objective is to measure temperature from room temperature to about 250°C using a thermistor. The thermistor resistance is a extremely non linear. It is approximated by a negative exponential of the reciprocal of absolute temperature.

$$R = R_0 e^{B \cdot (1/T - 1/T_0)}$$

R<sub>0</sub> is resistance at known temperature T<sub>0</sub>, in this case 25°C, expressed in Kelvin. Beta is a second parameter of the thermistor which can be calculated if you know the resistance at two different temperatures or can be found on the data sheet.

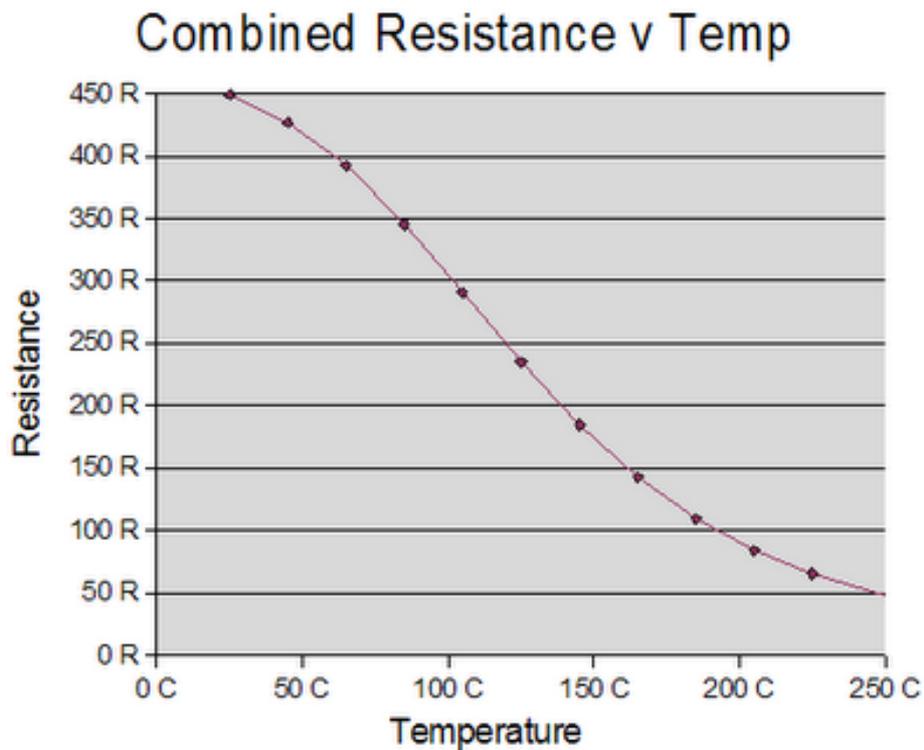
The RepRap thermistor is an Epcos B57540G0103+, data sheet [here](#). R<sub>25</sub> is 10K and beta is around 3500. Several values are given on the datasheet for different temperature ranges illustrating that the above equation is only an approximation. Here is a graph of its resistance against temperature :-



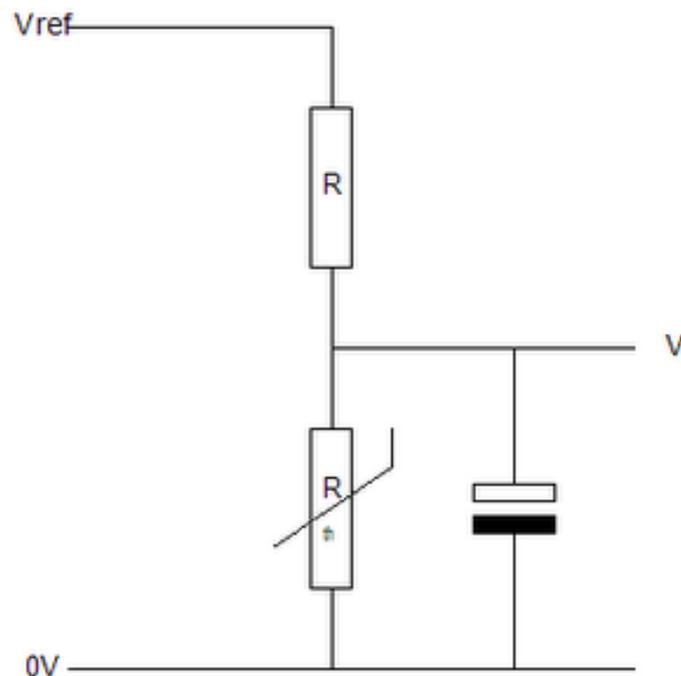
This can be made more linear by putting a fixed resistors in parallel. The magic value to use appears to be the value of the thermistor at the middle of the temperature range. In this case it is about 470 . Here is the resulting combined resistance, the formula for two resistors in parallel is :-

$$1/R = 1/R_1 + 1/R_2$$

I.e. the total conductance is the sum of the two conductances.



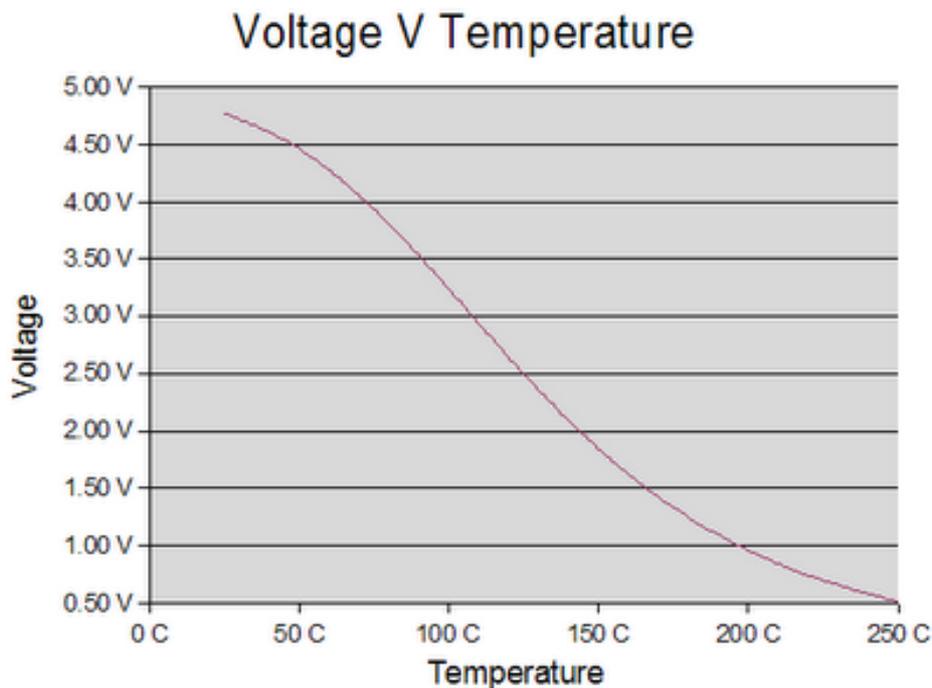
The resulting resistance is a lot more linear, however to measure temperature with an ADC we need a voltage rather than a resistance. This is easy, instead of wiring the resistor in parallel connect it in series to a voltage source equal to the full scale voltage of the ADC.



The voltage across the thermistor is then :-

$$V = V_{ref} \cdot R_{th} / (R + R_{th})$$

Here is a graph of the the output voltage when Vref is 5V.



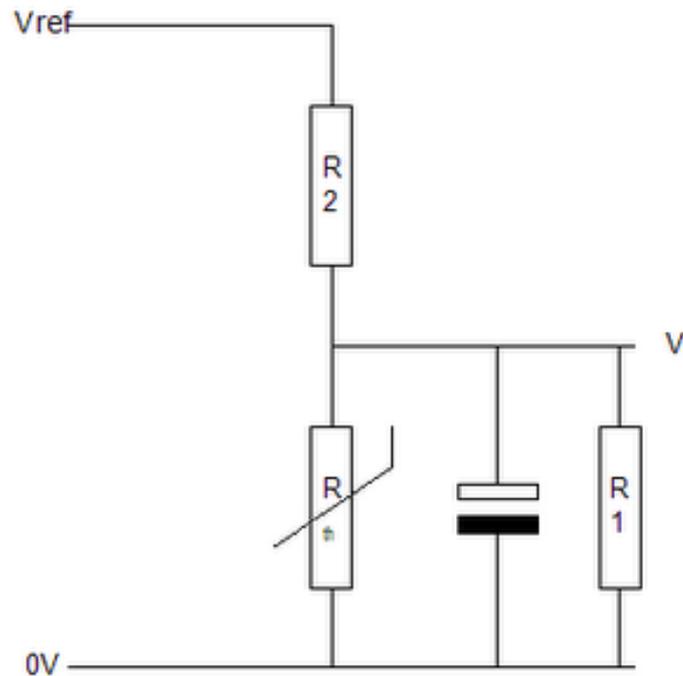
Note that the voltage decreases as the temperature rises. This could be inverted by swapping the resistor and thermistor but I prefer to keep one end of the thermistor at 0V so I can use single screened cable. It is also a good idea to put a capacitor across the ADC input to filter out any noise when using long leads like RepRap does. I used a 10uF tantalum bead.

Another consideration is how much power is dissipated in the thermistor as it will cause heating and alter the reading. The maximum dissipation will occur when its value equals the value of the resistor. At this point half the voltage is across the thermistor so the power dissipated in it is :-

$$P = (V_{ref} / 2)^2 / R$$

In the example above this works out at 13.3mW. The thermistor datasheet specifies a maximum of 18mW and a dissipation factor (in air) of 0.4 mW /K. I think this means that the temperature will rise by 33°C by self heating. The error would be less when not in air, but it is still perhaps a bit high. My system uses a  $V_{ref}$  of 1.5 volts which, because it is a square law, only dissipates 1.2mW giving a 3°C rise at the mid range temperature in air.

For a 5V system is is probably worth sacrificing some of the ADC resolution to reduce the self heating error. This can be done by using two resistors :-



The full scale voltage is now :-

$$V_{fsd} = V_{ref} * R1 / (R1 + R2)$$

We also want the source impedance of this voltage, which is R1 in parallel with R2, to be 470 .

$$1/R = 1/R1 + 1/R2$$

Solving these simultaneous equations gives :-

$$R1 = R / (1 - V_{fsd} / V_{ref})$$

$$R2 = R * R1 / (R1 - R)$$

So for  $V_{fsd} = 1.5V$ ,  $V_{ref} = 5V$  and  $R = 470$ :

$R1 = 671$  and  $R2 = 1569$  , preferred values are 680 and 1K6.

And finally here is the Python code to work out the temperature :-

```
from math import *

class Thermistor:
    "Class to do the thermistor maths"
    def __init__(self, r0, t0, beta, r1, r2):
        self.r0 = r0                # stated resistance, e.g. 10K
        self.t0 = t0 + 273.15      # temperature at stated resistance, e.g. 25C
        self.beta = beta           # stated beta, e.g. 3500
```

```

self.vadc = 5.0                # ADC reference
self.vcc = 5.0                # supply voltage to potential divider
self.vs = r1 * self.vcc / (r1 + r2) # effective bias voltage
self.rs = r1 * r2 / (r1 + r2)    # effective bias impedance
self.k = r0 * exp(-beta / self.t0) # constant part of calculation

def temp(self,adc):
    "Convert ADC reading into a temperature in Celcius"
    v = adc * self.vadc / 1024    # convert the 10 bit ADC value to a voltage
    r = self.rs * v / (self.vs - v) # resistance of thermistor
    return (self.beta / log(r / self.k)) - 273.15    # temperature

def setting(self, t):
    "Convert a temperature into a ADC value"
    r = self.r0 * exp(self.beta * (1 / (t + 273.15) - 1 / self.t0)) # resistance of the
thermistor
    v = self.vs * r / (self.rs + r) # the voltage at the potential divider
    return round(v / self.vadc * 1024) # the ADC reading

```

# GM3 motor suppressor

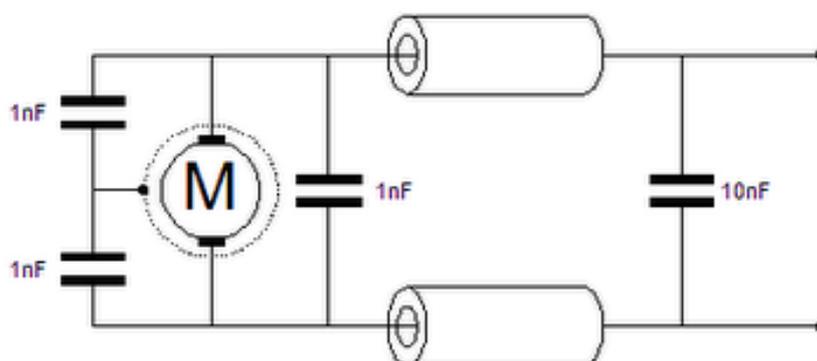
Saturday, 13th October 2007 by Nophead

I have also been asked for more details on my motor suppression circuit that I first blogged in [dc-to-daylight](#), so here goes :-

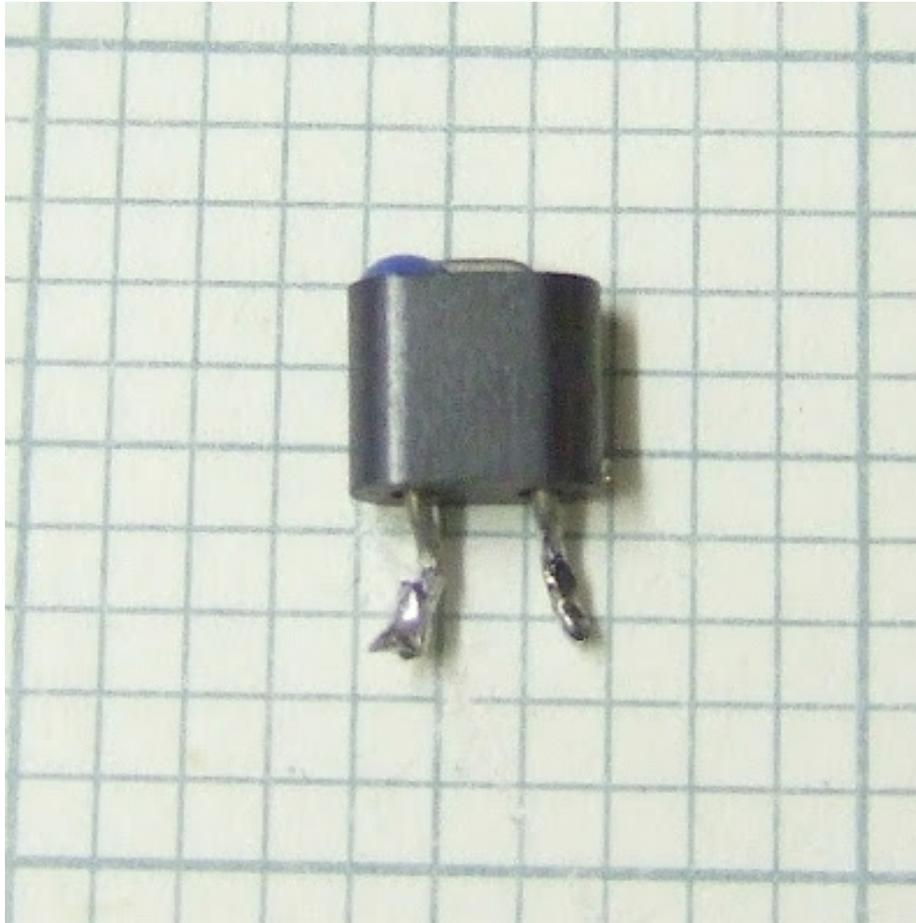


The Solarbotics GM3 generates large amounts of RF noise from 20MHz up to at least the TV band, which is 470- 850MHz in the UK. I know this because I can see the 20 MHz on my scope and it was also affecting our TV reception.

This is the circuit I used :-



The 1nF capacitors were axial ceramics and the 10nF was a radial ceramic, mainly because that is what I had to hand. I don't know the spec of the ferrite beads because I salvaged them from an old disc drive. Here is what they look like though :-

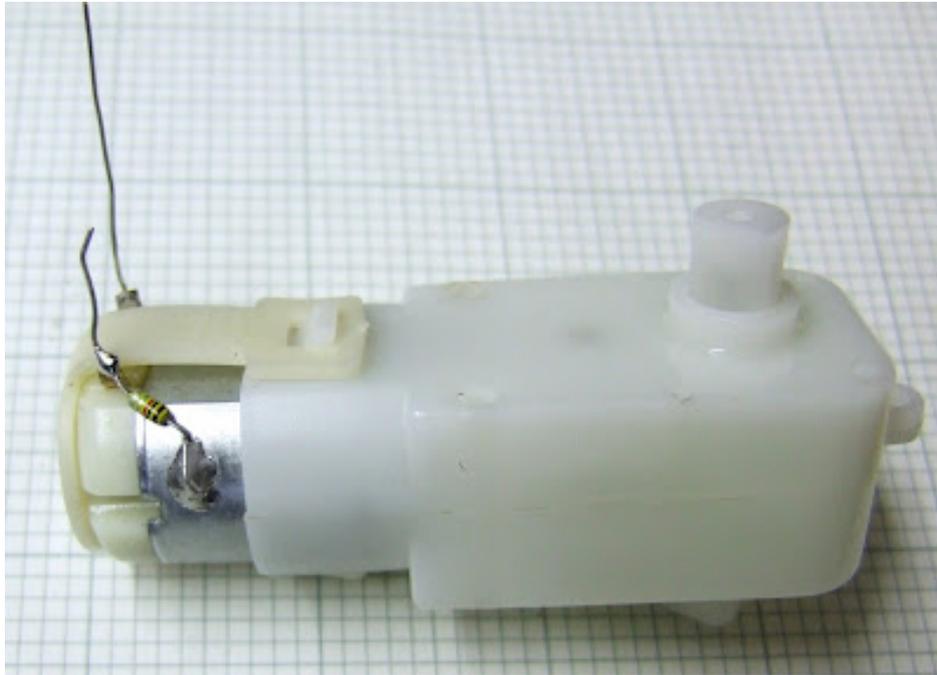


They should be a low Q type rated for at least 1A. The current rating is not so much about how much current they can carry but about the point where the magnetic field saturates the ferrite and the inductance disappears.

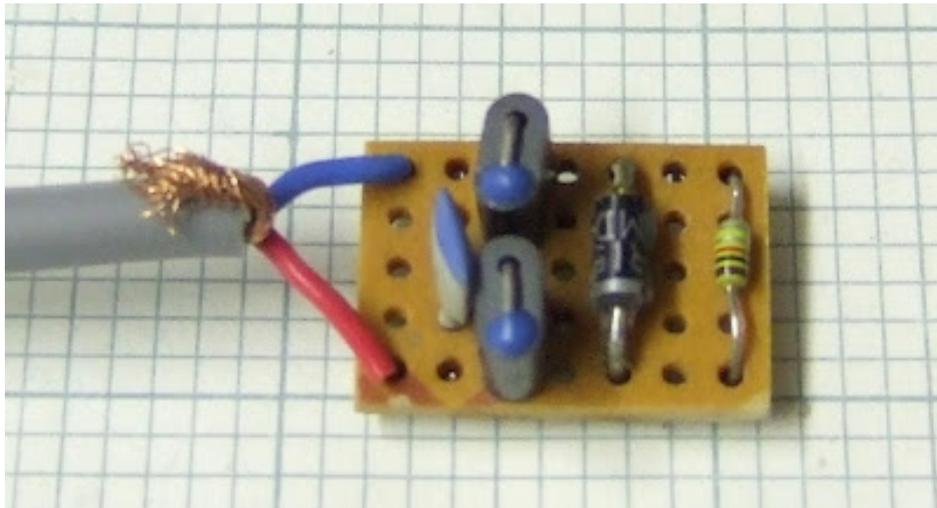
We want them to have a high impedance from 20 MHz to 800 MHz. I don't have much knowledge in this area but think this is quite a big ask for a ferrite and that I fell lucky with these. To get more impedance at the low frequency end it is normal to increase the number of turns to increase the inductance which is proportional to their square. The problem with that is that it increases the capacitance, reducing the attenuation at the high frequency end.

These beads are a good compromise: they have nearly a whole turn compared to a straight through bead which is half a turn, hence four times the inductance, but the wires maintain 0.1" separation so minimizing the capacitance.

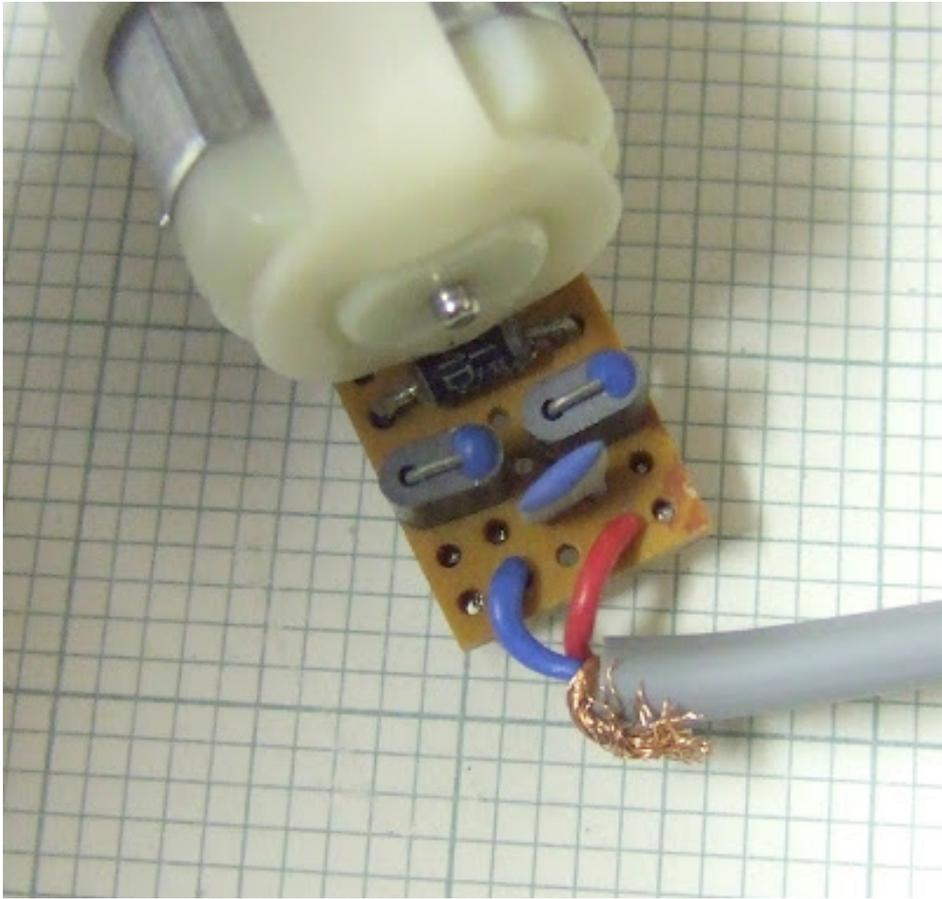
The first two 1nF capacitors are soldered to the motor case. This is easier than you might imagine because steel is such a poor conductor of heat compared to copper, although it has to be said I am using a 50W temperature controller soldering iron. I cleaned the area first with a PCB cleaning block.



This is the rest of the circuit before it was soldered on top of the two capacitor leads. Spot my mistake!



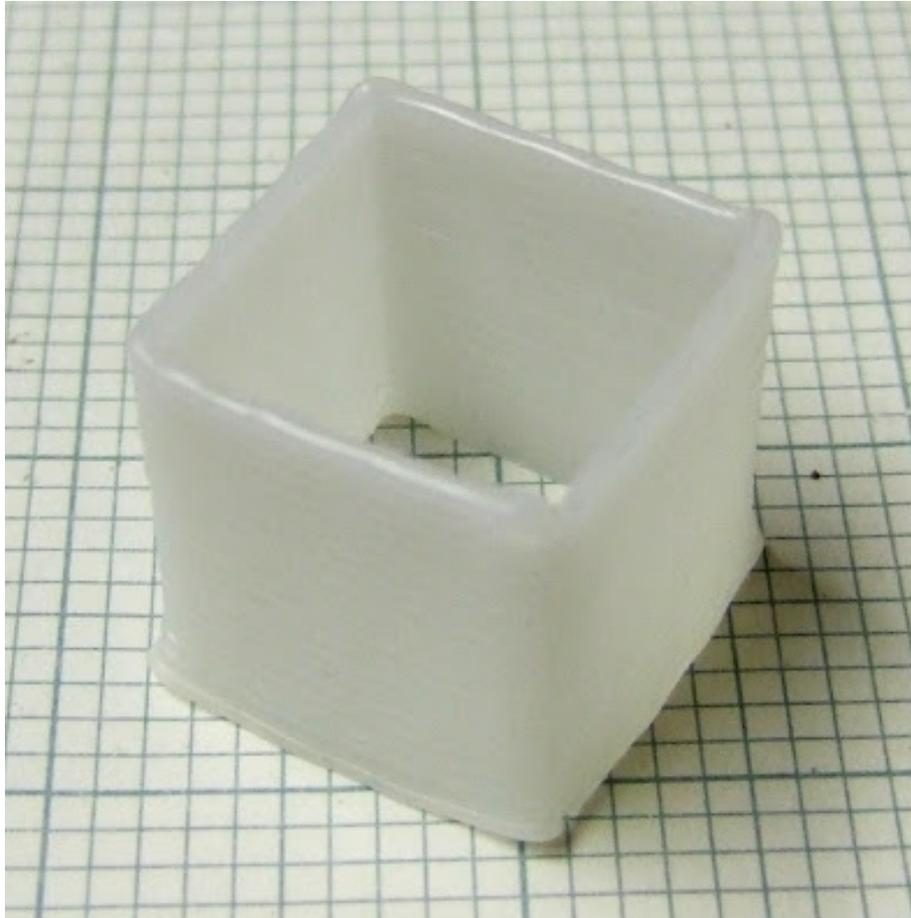
Ignore the back emf diode, it is specific to my controller and should really be part of it. I used twin screened cable with the braid grounded at the controller end and left unconnected at the filter end.



# Scaling new heights

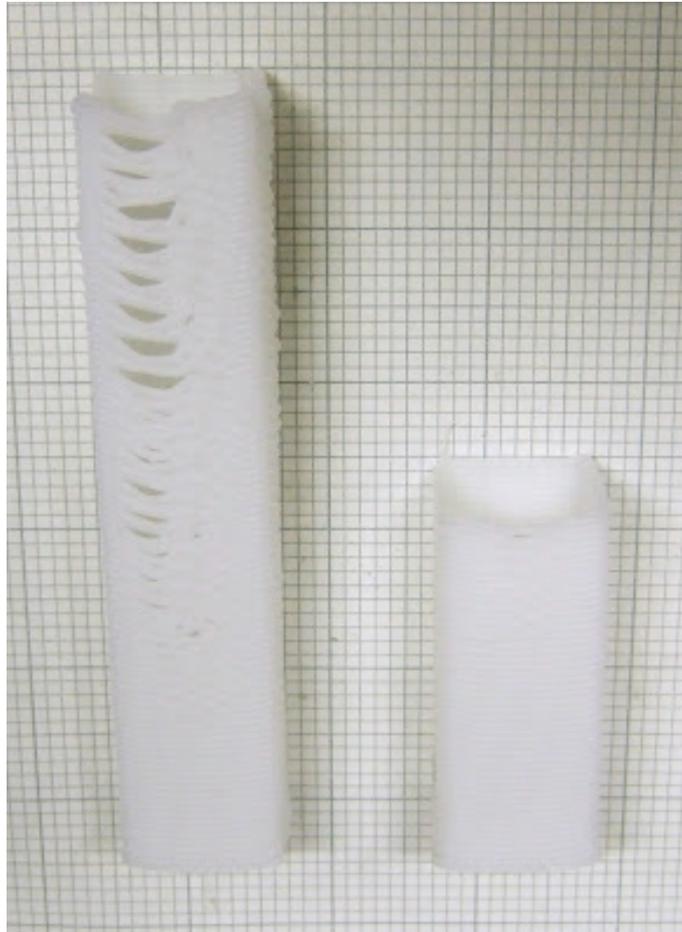
Tuesday, 16th October 2007 by Nophead

In my article [laying-it-on-the-line](#) I showed how I arrived at this test shape, a 20mm open ended cube :-

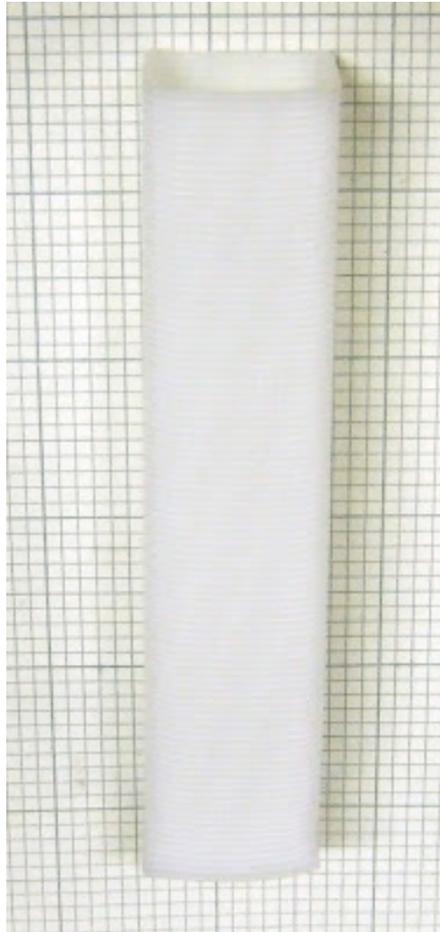


I decided to try different sized shapes to see how the process scales. It turns out that it doesn't and 20mm cubed is the magic size that is easiest to make!

The first thing I tried was taller :-

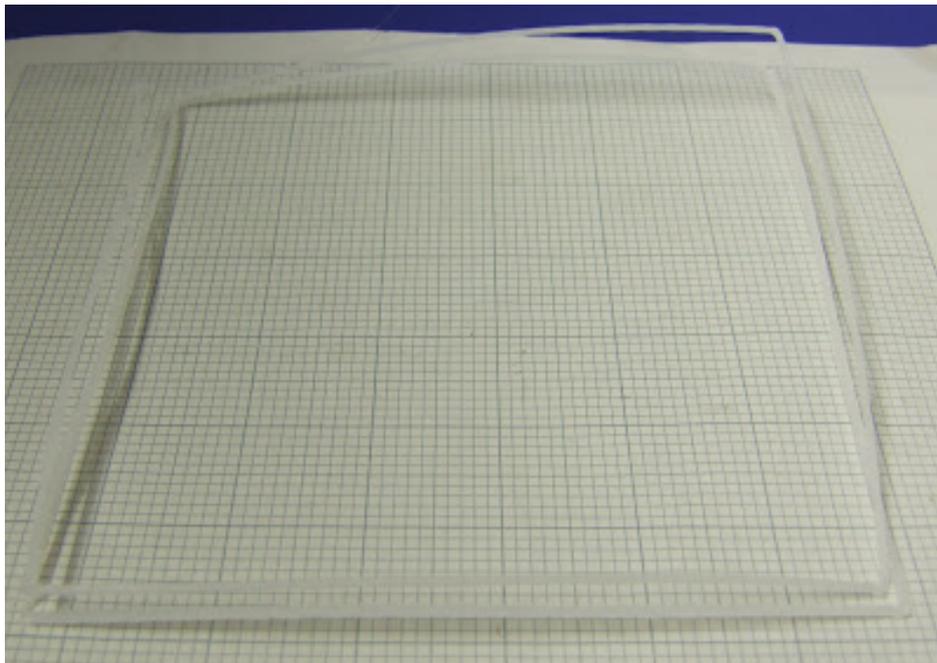


As you can see at 50mm tall it is starting to sag and 100mm is hopeless. The problem is that as the height increases, the plastic already laid down contracts as it cools and leaves the nozzle high and dry. I fixed that by reducing the Z increment from 1mm per layer to 0.95mm. That allowed me to make a good 20 x 20 x 95mm square tube :-



I presume with this increment I can keep going up, but who knows, I thought that at 20mm!

Next I tried low and wide. This was an attempt to make 120 x 120 x 20mm :-

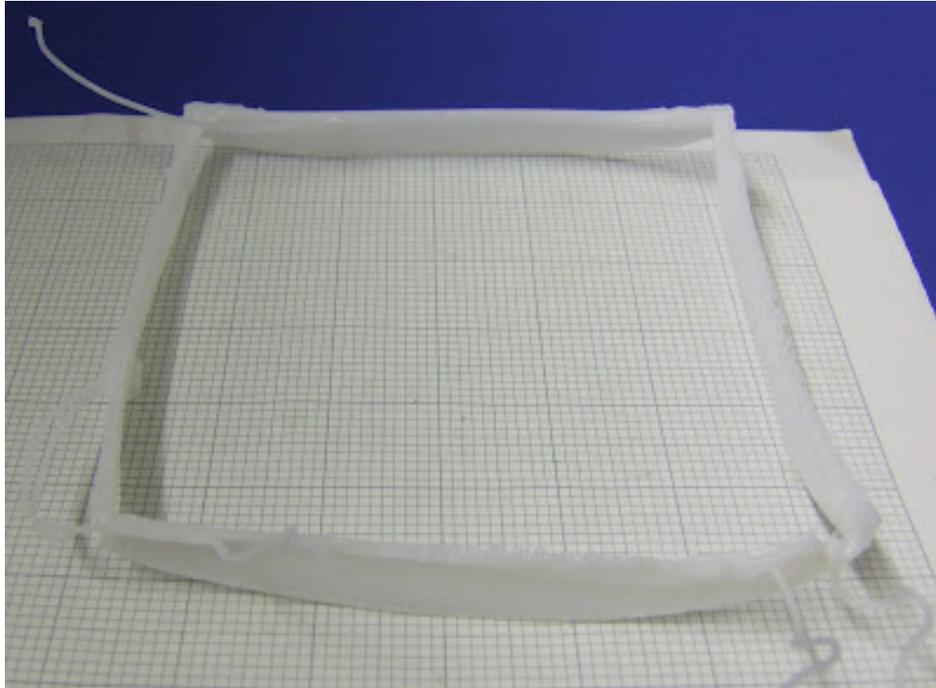


I stopped it when the first two layers failed to weld. This was because with an object this large, by

the time it has traced the perimeter to start the next layer, the first layer has cooled down to room temperature. In my post sticking point I predicted that to make an instantaneous weld between molten plastic and plastic at room temperature requires the molten plastic to be at temperature

$T = 2 \times T_m - T_r$ , for HDPE and 20°C this means about 240 - 250°C.

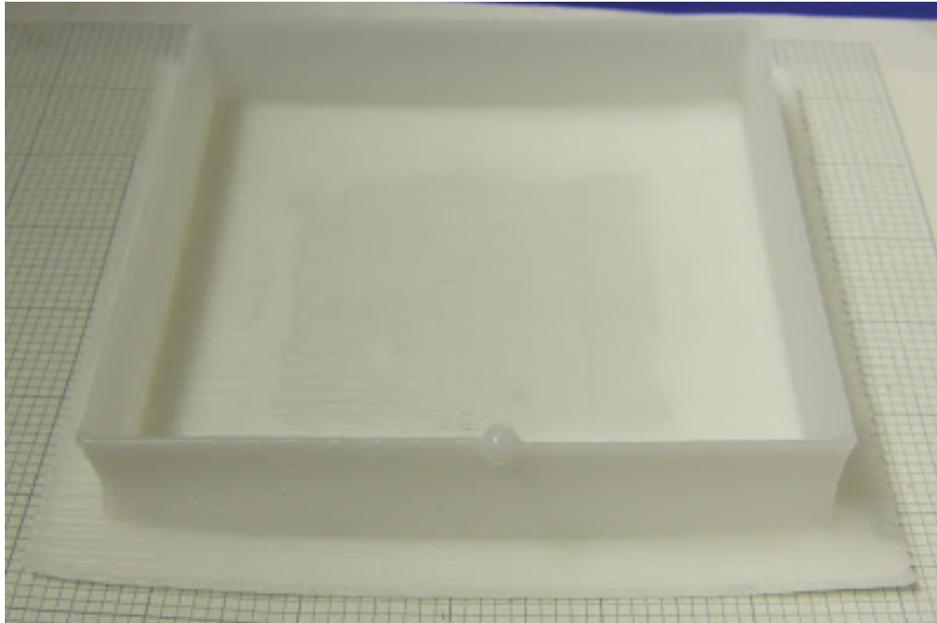
I set my extruder to 240°C and made this mess :-



I don't like running the extruder that hot because, although HDPE is not supposed to burn until 350°C, it smells like burning plastic and the end of the nozzle is glazed black. Also, the toothbrush that wipes the nozzle is showing signs of melting.

The object came unstuck from the foam board because of the extreme corner curling due to shrinkage. This is a fundamental problem with HDPE and room temperature FDM. HDPE shrinks about 2% when it cools from its melting point to room temperature. Commercial FDM machines use ABS, which has a lower shrinkage, and they keep the work piece in an oven close to the melting point. That means the hot plastic does not need to be so much hotter than the melting point, and most of the shrinkage occurs after the object is complete. The problem here is that the first layer cools and shrinks before the next layer lands on top. The next layer is bigger when it welds on top but then it shrinks, contracting the bottom layer more. Each subsequent layer increases the tension on the layers below. The bigger the object is, the worse the effect is because the mismatch between the size of the hot layer and the cold layer below it is bigger in absolute terms.

Following in Forrest's footsteps I tried laying down a raft of HDPE first to anchor the object to the foam base. The raft is 120 x 120mm but the object is now only 100 x 100 x 20mm.



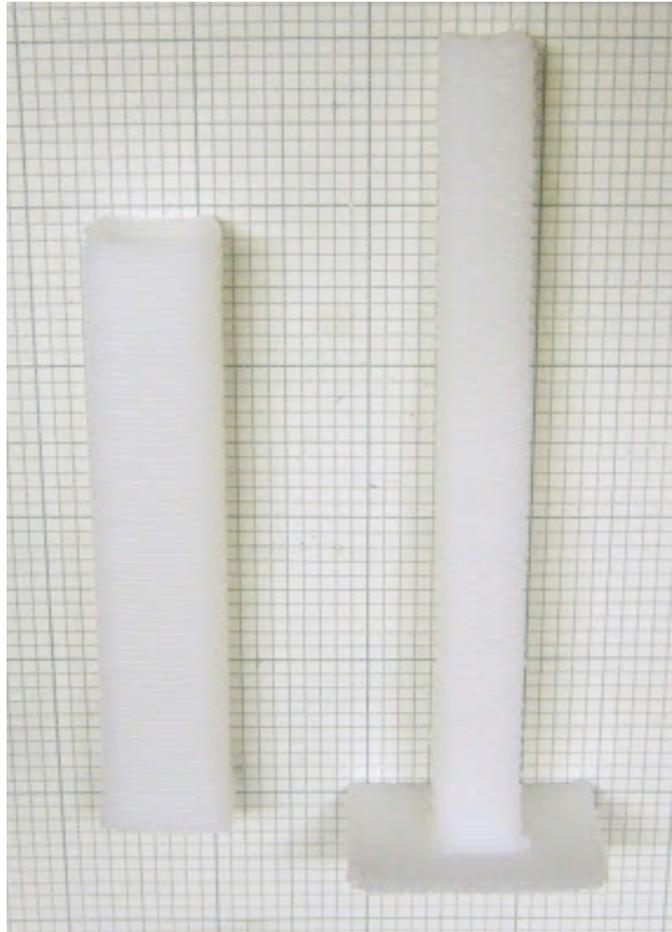
As you can see that gives a big improvement but it wasn't strong enough to hold the corners down fully. A bigger raft, and perhaps a second layer might help but as it was an hour to build the raft and half an hour to build the object I didn't bother trying again. The blob, by the way, is where the firmware crashed on the last layer!

Here are some 40 x 40 x 20mm tests made with rafts, the second one had a bigger raft:-



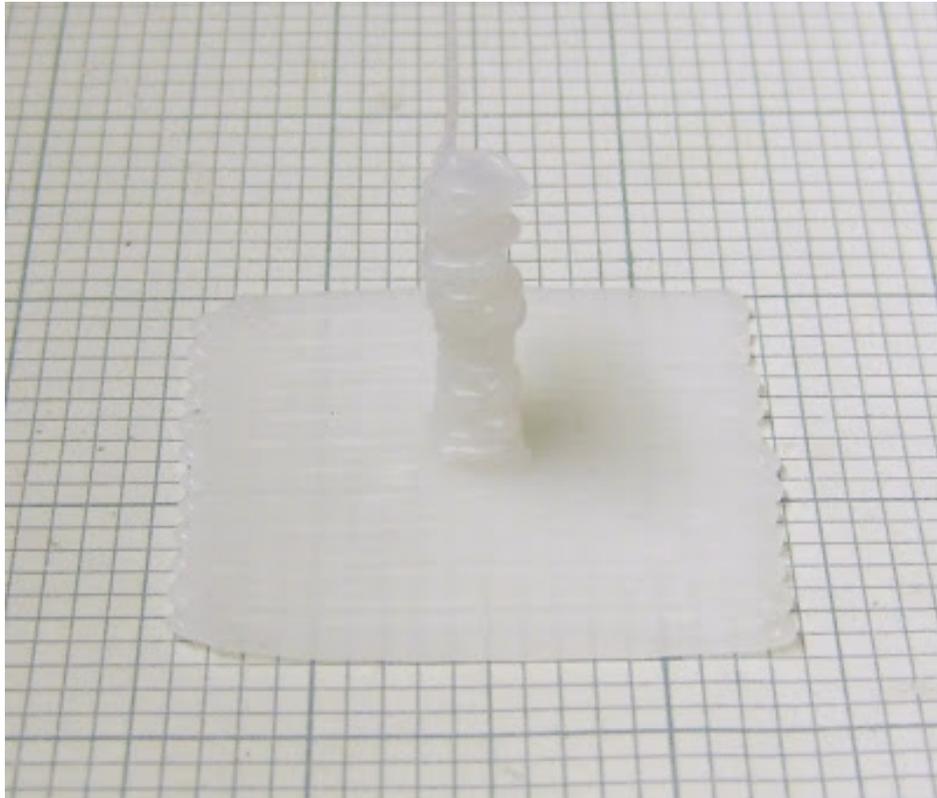
Here the corner curl with a raft is comparable to the 20 x 20 x 20mm test without a raft showing how this effect gets dramatically worse as width increases.

Next I tried tall thin objects :-



Both were made on rafts and, the first is 15 x 15 x 75 mm, the second is 10 x 10 x 100mm. The photo is not very good but they both flare towards the bottom. The one on the left has an untidy surface as each layer is not well aligned with the layer below it and the one of the right has a completely wavy surface like basket work.

The reason for this is that because the perimeter is shorter, the layer below is still molten when the next layer is extruded on top of it. It moves around giving an untidy surface and also does not resist the contraction of the layer above. The bottom few layers are the correct size because they are welded to the solid raft but the layers above are too small as they have contracted inwards. A 5 x 5mm test shows this effect even more :-



The only way around this is either to wait for the layer below to cool, speed up its cooling with a fan, or extrude very slowly. I decided to experiment with a fan. It was immediately obvious that if you have a fan blowing near the nozzle you have to insulate it otherwise it doesn't reach its target temperature.

The RepRap design uses fiberglass wool but I wanted to be able to see the state of my heater so I decided to make a transparent cover. I started with a plastic test tube, donated by my wife, which used to contain bath salts.



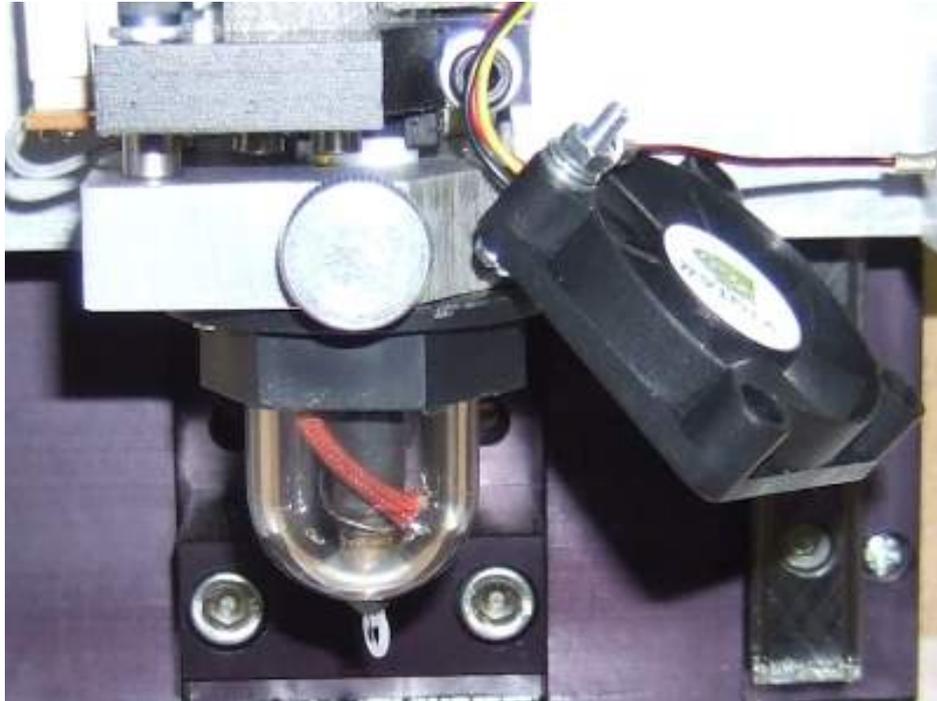
I cut the end off this and drilled a hole to clear the nozzle. I converted a large plastic nut into a mounting flange by stripping out the thread on my lathe so that it was a push fit.



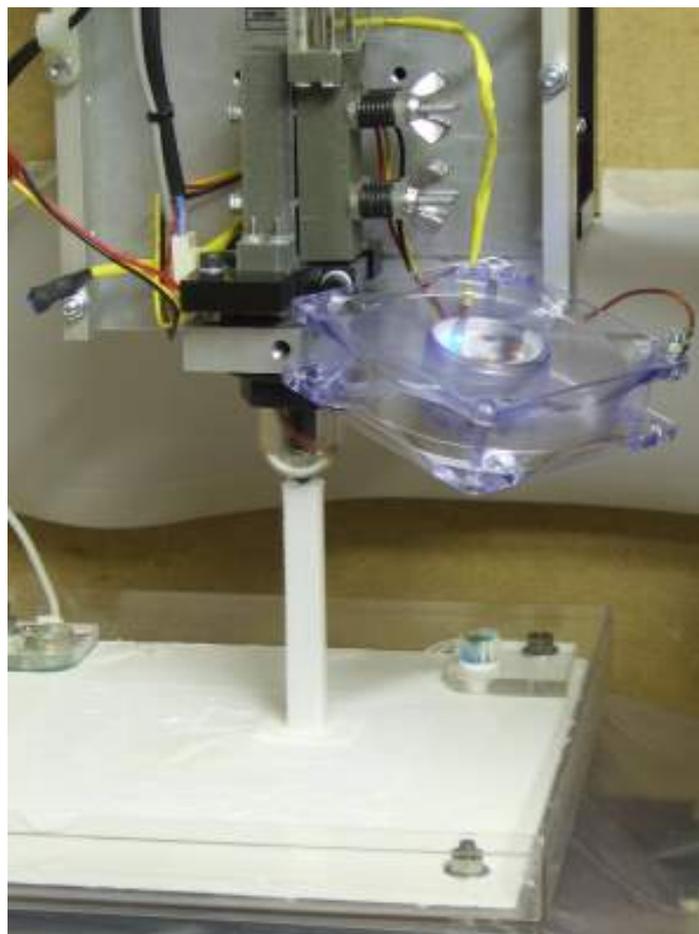
Here it is mounted on the extruder :-



The first fan I tried was a small North bridge cooling fan. It was so light that I could mount it on a stiff wire attached by ring tail crimps and bolts. :-

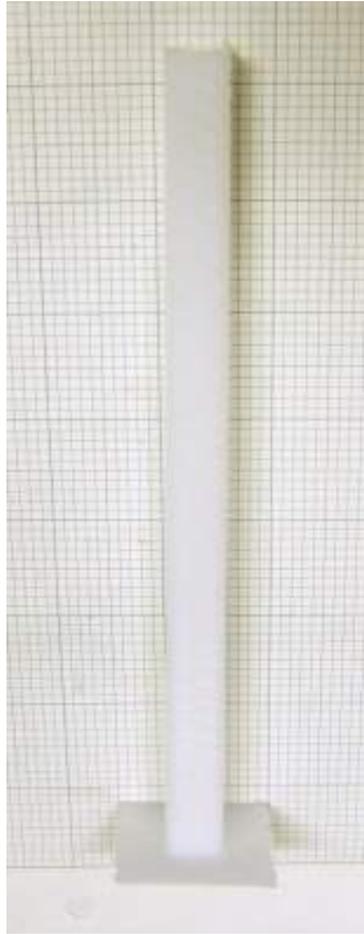


Unfortunately it wasn't very powerful so the next fan I tried was a PC case fan complete with speed control and blue flashing LEDs.



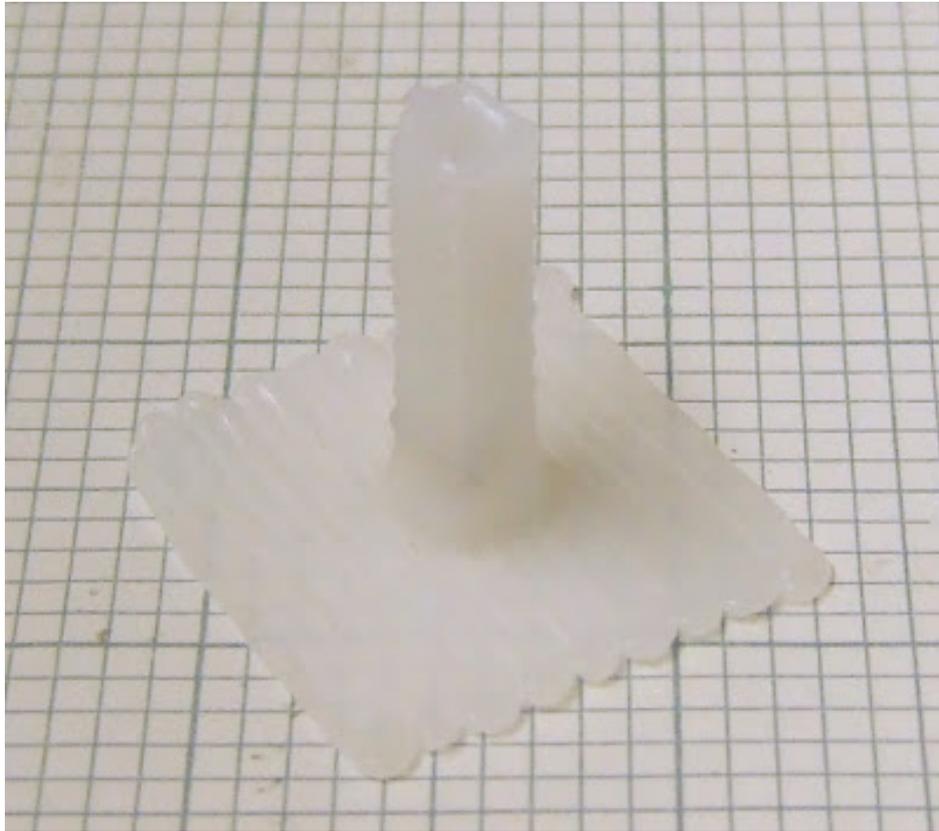
This worked a lot better but it is difficult to get it as close as I would like it. Here is the tallest thing I

have made so far, it is 10 x 10 x 150mm. At this point I changed to 4mm per second travel and a feed rate to give a 1mm filament. I found that you can get finer filament just by stretching it as it leaves the nozzle so the work I did with flow rate and filament size is not really relevant. I had to reduce the layer height to 0.8mm.



This worked well on the windward side, with a nice tight corner, but not so well on the leeward side. The corner away from the fan is more rounded and the layers are less tidy. A cross section shows that the two sides cooled by the fan are straighter and longer.

The 5 x 5 x 20mm test is much improved but its surface area is so small that the fan fails to keep it cool enough. I think the only option with something as small as this is to slow down, and possibly drop the temperature.

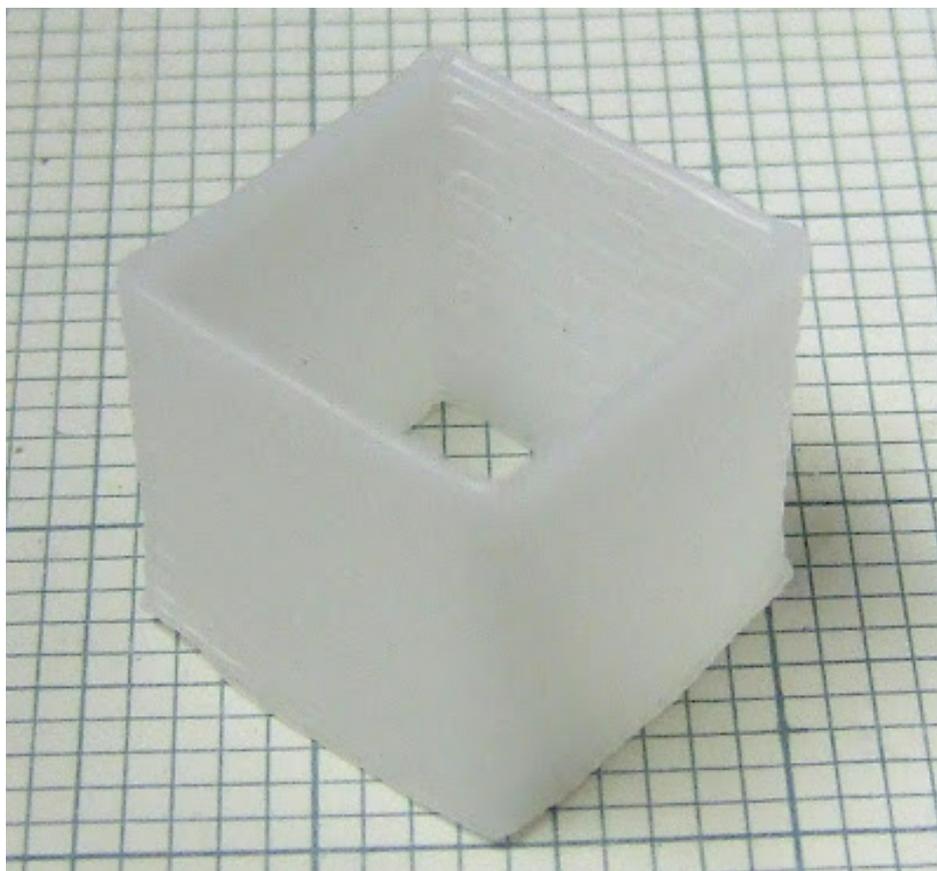


Again the leeward side is not as good. The filament short cuts the corner because the layer below is not strong enough to hold it in place. I think to make the fan effective a cowling and duct is needed to get a strong flow of air directed downwards around all sides of the nozzle.



I have noticed that there is always an excess of material at the corners. This is because the head makes a perfect right angle but the filament has a minimum bend radius and takes a short cut. I am not sure how to compensate for this. I can't really pause the extruder because its response is too slow, so I either have to speed the head up as it takes a corner, or perhaps make it move in an arc that matches the bend radius rather than a right angle.

And finally here is an improved version of the magic 20mm cube :-



This is with the benefit of a raft, finer filament and fan cooling. The corners are a bit sharper and the corner curling a bit less. The reasons why this turned out to be the optimum shape are :-

1. It is small enough that the filament does not cool too much when you go round it.
2. It is large enough to make it long enough to traverse so that it does not stay too hot.
3. It is short enough for the fan to be able to cool the back wall from the inside as well as the front.
4. It is small enough for corner curling to not be too extreme.

From these experiments I now think I have a good understanding of how the parameters: temperature, flow rate, traversal rate, z increment and fan use affect the result. I have only looked at thin walled boxes, I expect solid objects to add more thermal and contraction issues.

The only reason I am using HDPE is that it seems to be the only thermoplastic filament I can buy off the shelf in the UK without getting it specially made.

With a bit of trial and error I expect I could make the machine produce a wide range of shapes and

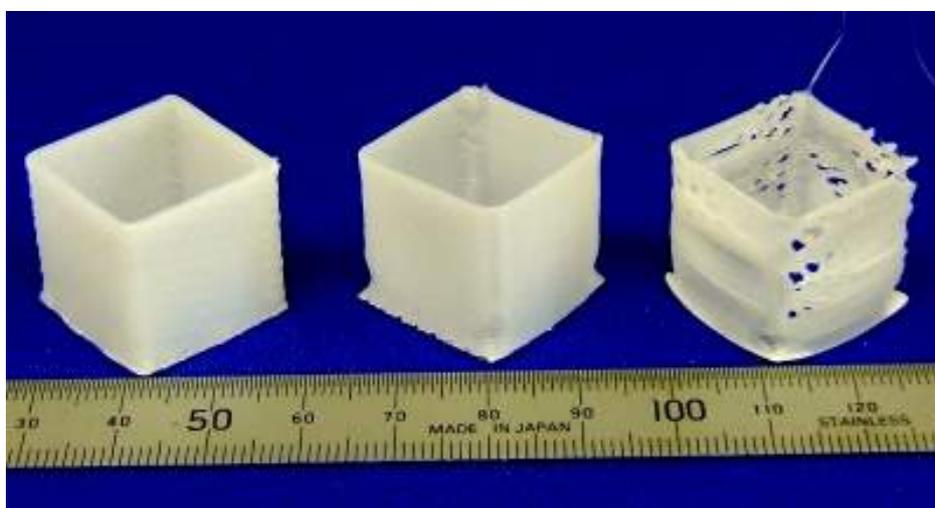
some useful objects but therein lies the problem. It is not supposed to be trial and error. The dream is to be able to input an arbitrary 3D model, of any size within the build volume, and have the item appear a few hours later. At the moment I can't see how that can happen with room temperature extrusion of HDPE. Its melting point is too high and its contraction too great. Managing the temperature of the object being built is very tricky as the features of the object vary from large to small.

# Stretching a point

Tuesday, 23rd October 2007 by Nophead

In his article: [x-idler-bracket-continued](#) Vik Olliver alluded to the fact that you can extrude filament with a smaller diameter than the hole in the nozzle. I did some experiments to see how fine I could go. In fact the final filament diameter is simply determined by the feed rate of the extruder and the travel rate of the nozzle, or in my case the bed. The filament stretches to the length that matches the rate of travel while it is still liquid. You can then calculate the mean diameter from the volume of material extruded. The nozzle height has to be a bit less than that mean diameter and then the width becomes a bit wider.

Here are three 20 x 20 x 20 open cubes with different wall thicknesses :-



The first was 1mm diameter filament extruded at 4mm per second with a height of 0.8mm giving a wall thickness of about 1.2mm.

The second was the same feed rate but with the extruder traveling over the bed at 16mm per second to give 0.5mm filament, the same as the nozzle hole diameter. The height was set to 0.4mm giving a wall thickness of about 0.6mm. As you can see it warps more but I expect it would behave if it was building a solid object. The bottom layer which was stuck to the table has better corner definition.

The third attempt was 0.35mm filament extruded at 16mm per second with a height of 0.28mm and a width of about 0.5mm. As you can see holes started appearing but I think that was just because the sides buckled so badly. Interestingly the holes can be bridged by filament above that needs no support. Again, I think this would be OK making solid objects, or at least objects with thicker walls.

This is really good news as it means I can get down to the sort of resolution commercial machines get (0.25mm) without having to have a very small nozzle aperture, which would limit the flow rate. It remains to be seen what effect stretching has on the polymer but as it is still liquid at that point I

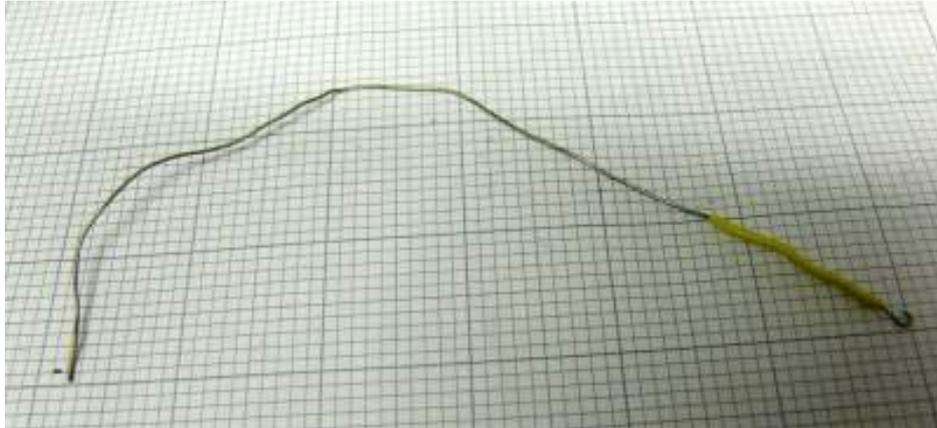
think it wont increase the contraction much, if at all. It does mean I need very fast head movement to keep up the deposition rate, about 64mm per second. I think my machine will do that if I reconfigure the steppers for speed rather than torque, a simple one wire change.

# They don't like it up 'em!

Tuesday, 23rd October 2007 by Nophead

How is this for bad luck :-

I was trying to connect a scope probe to the far side of a two row connector on my machine. I made a small hook from a piece of wire with a bit of insulation to get it past the front row.



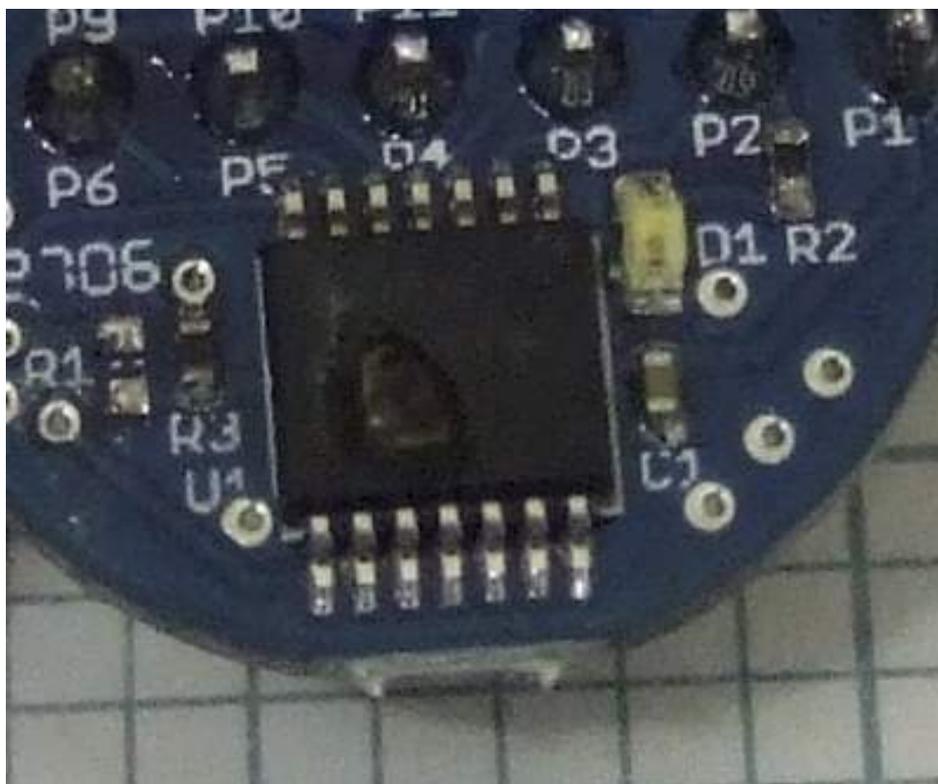
I inserted this with the power turned off. Unfortunately, and almost unbelievably, the far end of the wire manage to find its way into a hole leading to the mains live terminal on my solid state relay. That was the only thing on the live side of the mains switch.

Massive bang! Blew the crap out of HydraRaptor and my ADSL router. My PC is crippled is well, it no longer runs at the correct front side bus speed and insists I haven't got an 80 pin IDE cable.

This is the CPU of my axis controller :-



And this the micro from my extruder controller :-



I expect all the rest of the electronics is fried as well, so pretty much the end of HydraRaptor. The

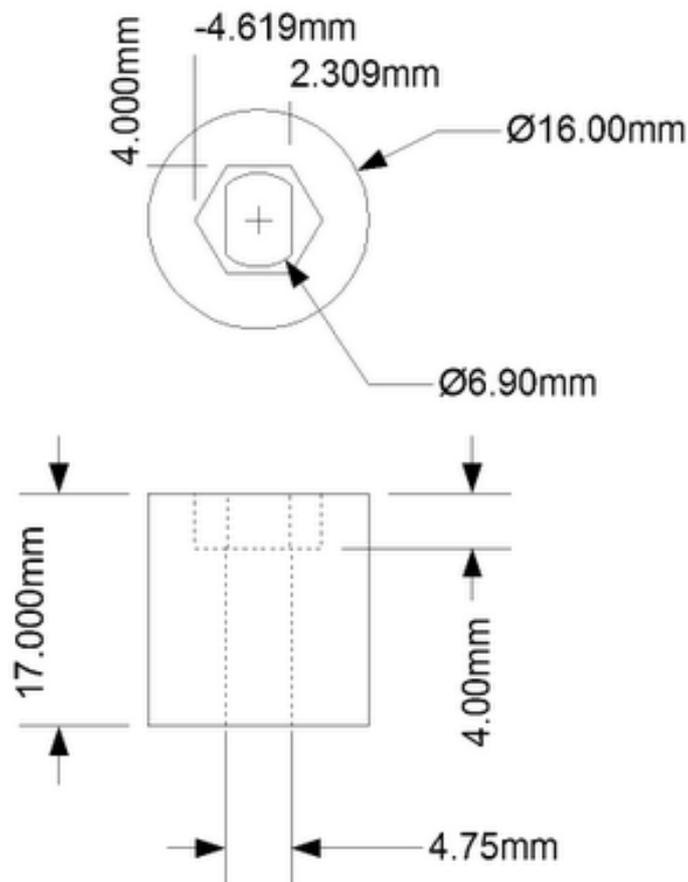
only lucky thing was that I was holding the insulation, otherwise it might have been the end of me as well!

# Extruder dimensions

Saturday, 27th October 2007 by Nophead

I have been asked for dimensioned drawings of the extruder. I made these by manually inspecting the 3D models in ArtOfIllusion. It is not the easiest application for extracting dimensions so I made 2D drawings in Visio which does have good dimensioning tools. I then made Python scrips to do the milling. My dimensions may differ in places but I did make the extruder from these drawings and it does work. I tightened up some of the hole clearances because my milling machine holds much tighter tolerance than FDM.

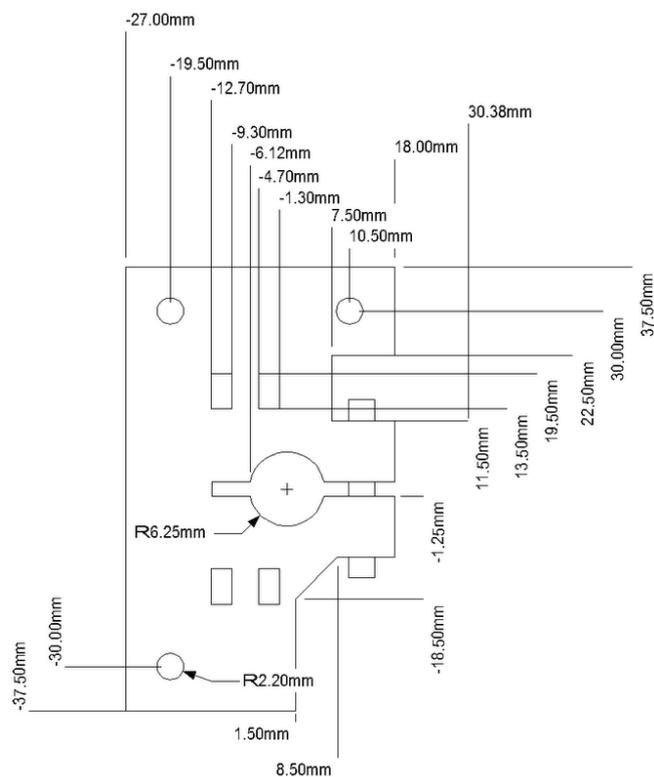
This is the motor shaft coupler. I adjusted the slot to suit my GM3 motor. I think there are now two versions of this part. The official design is tapered but this is not necessary with the offset motor mount so I simplified it to a cylinder.



Here is the finished article milled with a 2.22 mm bit. The step on the outside and in the shaft slot are there because my milling tool's shaft is wider than the bit, so to go deeper than 9mm I need to have some clearance. The material is some sort of metal loaded resin.



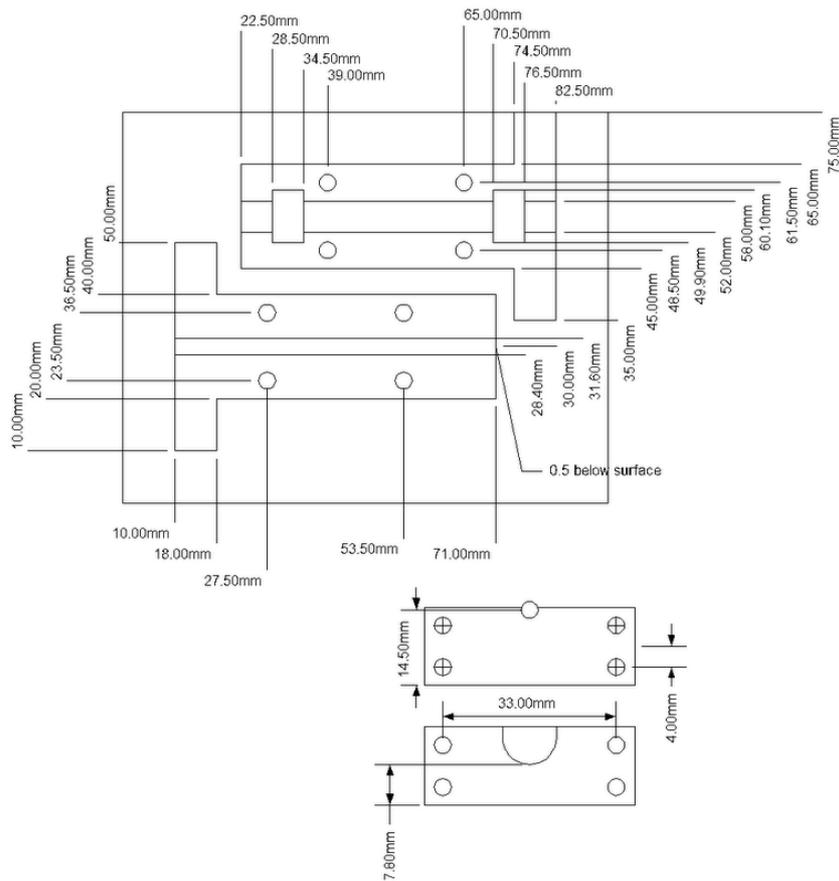
Here is the clamp drawing I used. It has now been superseded by a larger design. Note that I adjusted the hole for the PTFE to suit my 12mm rod. I think the official design was 10mm but is now 16mm. I also widened the slot to allow the 2.2mm milling tool to get in and added some extra mounting holes to suit my machine.



I milled it from 9mm Delrin.



Here is the pump drawing :-



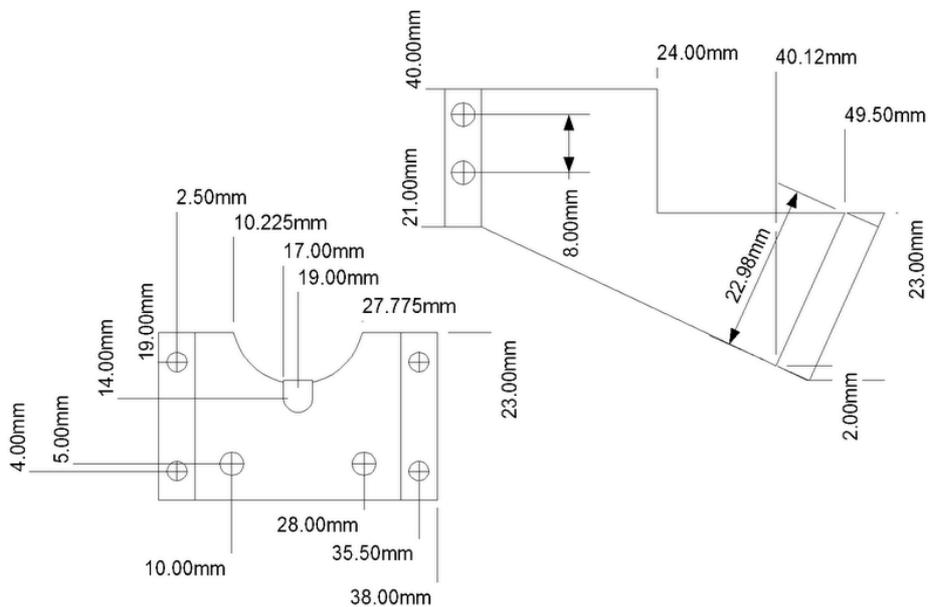
The poly channel on the official version slopes outwards at the entry but that is only needed for the version without the offset motor.

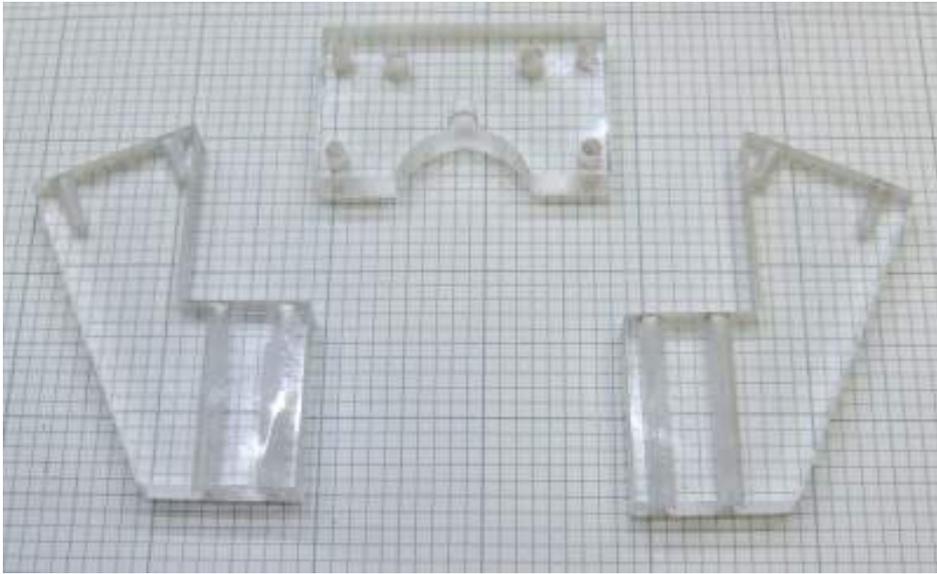
And here is the milled version :-



The material I used is not as slippery as CAPA so, to reduce friction in the channel, I smoothed it with emery paper, polished it with metal polish and sprayed it with PTFE dry film spray.

I split the motor mount into three pieces for milling from a sheet of 5mm perspex. I fixed the pieces together with M2.5 screws, tapped into the perspex.





If anybody wants the Visio source file it is here:- [forums.reprap.org](http://forums.reprap.org)

# Disaster recovery

Tuesday, 13th November 2007 by Nophead

I am pleased to say HydraRaptor is now back up and running after my accident where I connected 240V to a 3.3V logic input. I had to replace most of the electronics, which is annoying because I originally made it out of things I already had, so it cost me nothing, but replacement parts cost me around £180 and obtaining them set me back three weeks.

Things that were destroyed:

- My ADSL router: a friend kindly gave me a replacement.
- My PC's serial port: I replaced it with a USB to serial adapter.
- The Freescale DEMO9S12NE64 evaluation board that I used for my axis controller: next day delivery from Farnell.
- The EZ430-T2012 eval board that I used for the extruder controller, fortunately the spindle controller was not connected at the time so that survived.
- The ULN2803 and 7407 chips on my interface board.
- The optical shaft encoder chip on my extruder.
- The NEAT MDM7 stepper driver on the X axis. The only thing wrong with it was the direction input was not working. They are opto coupled so it should have been just a simple matter of replacing the opto, but the whole thing is potted in epoxy resin so it is impossible to fix. I managed to find a replacement on the web and I have got some spares on the way as well.

Things that survived:

- Both power supplies and all the local voltage regulators.
- The Y axis stepper driver.
- The X-Y table shaft encoders and Hall effect limit switches.
- The protected MOSFETs on the extruder controller.

I spent the time waiting for the stepper controller to arrive from the US improving my firmware. I fixed a long standing issue with timing: I was doing my Ethernet comms under interrupt and the stepper motor timing with a higher priority timer interrupt. Unfortunately, the 9S12 does not have nested interrupts, so the interrupt priority is pretty meaningless. I fixed it by moving my comms to the foreground as the machine has nothing else to do in the foreground but process commands coming from the network so there was no point in doing it with interrupts.

I also added acceleration and deceleration to my stepper driving software. I am aiming to lay down 0.25mm filament at 64mm/s. My XY table can easily move that fast but I didn't like the thump I was getting when it started and stopped. It's a bit much to ask it to accelerate a few kilograms to 64mm/s instantly! The datagram for the goto\_xyz command now includes a table of delays to use for the first and last n steps. It remains to be seen how much distortion I will get from not moving at constant velocity. At the very least the acceleration will be useful in speeding up the moves when it is not extruding.

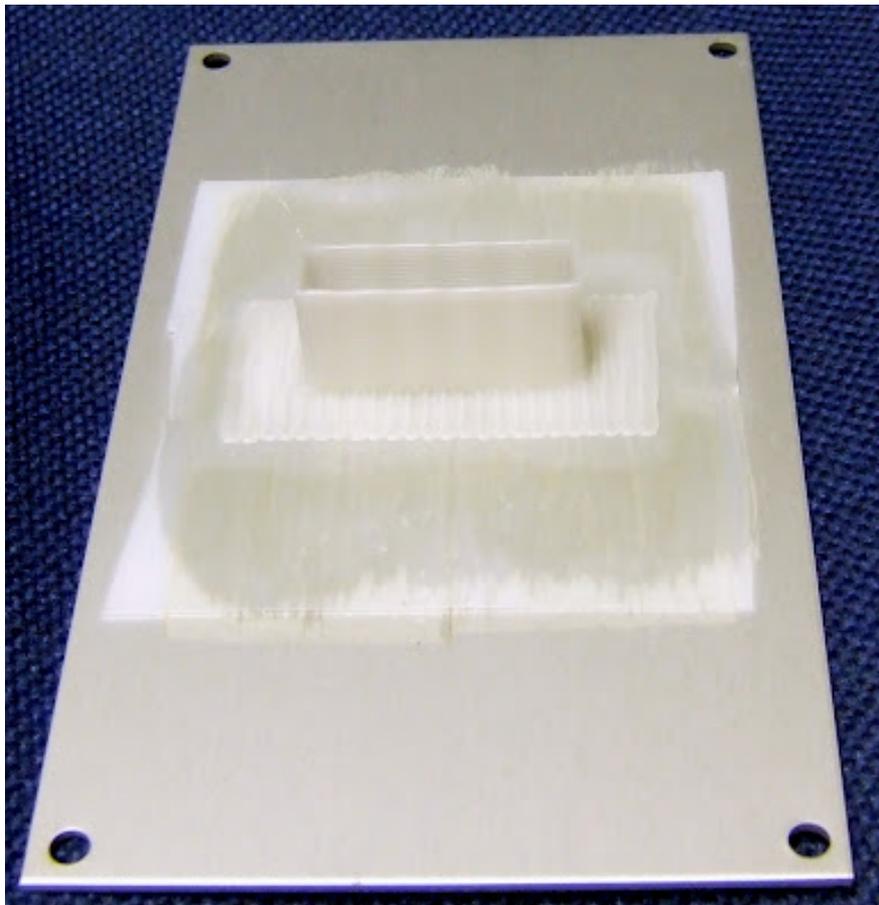
# Chopping up chopping boards

Sunday, 16th December 2007 by Nophead

Up until now I have been extruding HDPE onto foam board because it was the only thing that it sticks to well enough. However, it has a couple of failings: It is not strong enough to completely resist the warping caused by the HDPE and it is not reusable because the surface gets ripped off.

I have tried many other surfaces including various woods and metals (with and without primer), melamine and several other types of foam board but nothing worked. Obviously HDPE sticks to HDPE so I decided to investigate that further.

My first idea was to use a thin sheet of HDPE cut from a milk bottle. This makes a nice surface to extrude onto but the problem is holding it down. I first stuck it down with double sided tape but the heat melts the glue. Sticking it to a sheet of aluminium to take the heat away improved matters and I was able to get slightly less warping than with foam board.



To compare the warping on different base materials I made a test shape that is a 40mm x 10mm x 20mm open box with 1mm walls and measured how much the corners lift using a simple jig.



With foam board I was getting 0.83mm lift between corners and the middle. With HDPE stuck to aluminium I got 0.76mm. Not much better because the glue of the sticky tape stretches under the curling force.

I needed a thick HDPE base and I had heard that plastic kitchen chopping boards are made from HDPE. I bought a new one from ASDA which looks like this :-



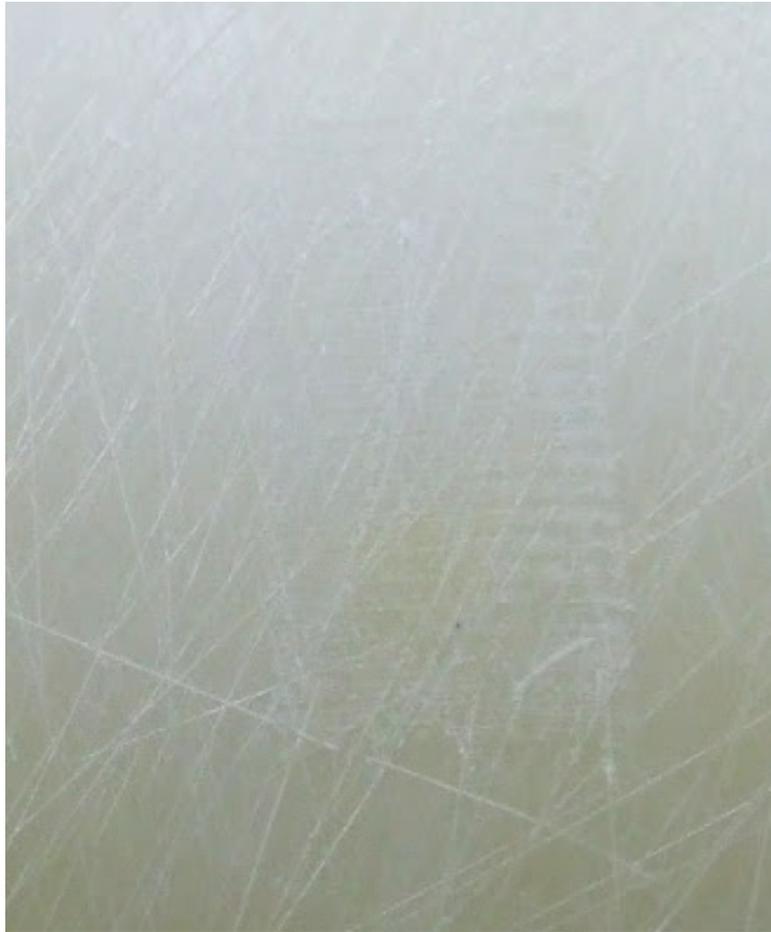
It is 5mm thick, opaque and quite rigid. I realised it was very different from the other chopping boards we have which I think came from IKEA.



These are 10mm thick and made from a softer, more translucent plastic. To find out which was HDPE I used the flow chart on this website [www.texloc.com/ztextonly/clplasticid.htm](http://www.texloc.com/ztextonly/clplasticid.htm). I concluded the thin hard one from ASDA is HDPE and the thicker softer one from IKEA is PP. HDPE seems to stick equally well to both of them but the HDPE one warped a bit when it was only held down with masking tape, so I decided to go with the PP one. I cut it up and bolted it down to my XY-table. It was a bit curved due to years of dishwasher use but bolting it down pulled it flat.



Surprisingly, if I lay down a raft at 200°C it sticks well but can be easily prized off again with a penknife. The board is marked slightly but it can be reused over and over again.



I extrude the object at 240°C so that it welds to the raft and itself, and I turn the fan on after the first layer so that the object cools to room temp as fast as possible.

The board is strong enough to hold the object completely flat while it is attached but when it is removed it does still curl a bit. I measured 0.44mm on my jig so that is about half the curling I was getting with foam board. Other than extruding onto a convex surface, I think that is the best that can be achieved for that shape with HDPE at room temperature. Here are the three tests side by side :-

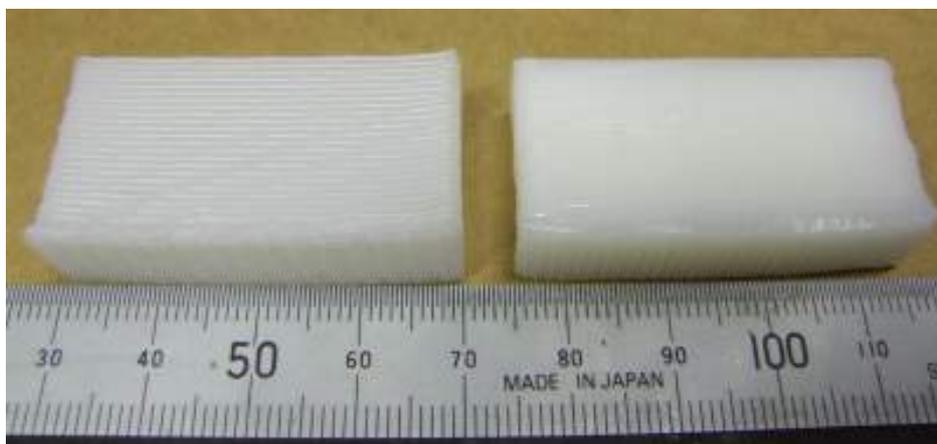


Next I will look at different solid shapes to see if they warp more or less.

# Warped

Wednesday, 26th December 2007 by Nophead

Having got an idea of the HDPE warping for thin walled open boxes, I decided to start investigating solid shapes. I made a solid block 40 x 10 x 20mm to compare with the open boxes of the same dimensions.



Obviously there are many ways to fill the interior so I started with the simplest, just alternate layers of horizontal and vertical zigzags. HydraRaptor seems quite happy extruding 0.5mm diameter filament at 16 mm / second. If extruded into free air it would actually be 1mm at 4mm/s, but that is too coarse, so I move the head at 16mm/s which stretches it.

From trial and error I have found that a good layer height to use is 0.8 times the notional filament diameter. If it is more, then as the lower layers shrink, the nozzle rises faster than the object and a gap develops. Once that happens the filament squirms about and does not follow the path of the nozzle accurately.

So the extruded filament is constrained to 0.4mm high. Measurements show the width to be about 0.6mm. Incidentally, if it squashed to a perfect ellipse with a height of 0.4mm then it would be 0.625mm wide to have the same area as a 0.5mm circle. I extrude the zigzag with a pitch of 0.6mm so that adjacent filaments touch, but it means the object is not actually completely solid. The space occupied by each filament is a rectangular channel  $0.4 \times 0.6 = 0.24\text{mm}^2$  but the cross sectional area of the plastic is  $\pi \times 0.25^2 = 0.20\text{mm}^2$ , so about 18% is air. I confirmed this by weighing the block. It weighs 6.5g but if it was solid HDPE then 8ml would weight about 8g. It takes about 45 minutes to make the object including laying a raft.

Before I tried it, I always imagined the amount of plastic deposited would have to exactly match the volume of the extruded object otherwise it would sag or bulge. I could never understand how FDM worked reliably. Now I know that the volume can be a bit less and the difference is made up by air. That means the amount of plastic deposited is actually not that critical, which is why RepRap can get away with an open loop extruder.

I measured the warping with the three nail jig that I showed in the last post. The thin walled box is

warped 0.44mm and the solid box has warped 0.87mm so that answers the question whether solid objects warp more or less. Note that the thin walled box is made with 1mm filament because 0.5mm filament is too thin to be self supporting.

I expect I can make a less warped block by extruding a thick base and then a less dense infill above that. Something else to try.

It is amazing how strong 10mm thick HDPE is. You don't often get to see plastics in that form. Most end products have optimised strength against cost by having thin walls and ribs etc.

# Cutting corners

Thursday, 27th December 2007 by Nophead

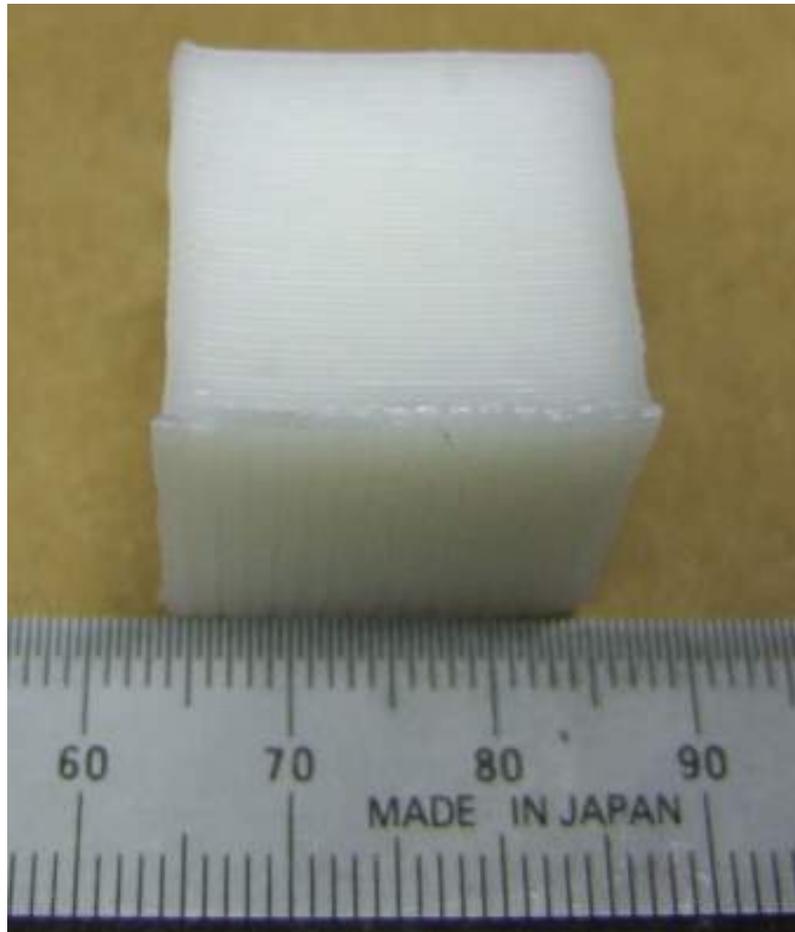
When making solid blocks with 0.5mm HDPE filament I noticed that the corners are not very accurate. The right hand edge of the 20mm cube below shows this effect at its worst :-



The problem is that, although the machine makes a perfect right angle, the filament appears to have a minimum bend radius and so cuts the corner. The amount it cuts the corner seems to vary from layer to layer giving rise to the rough edge.

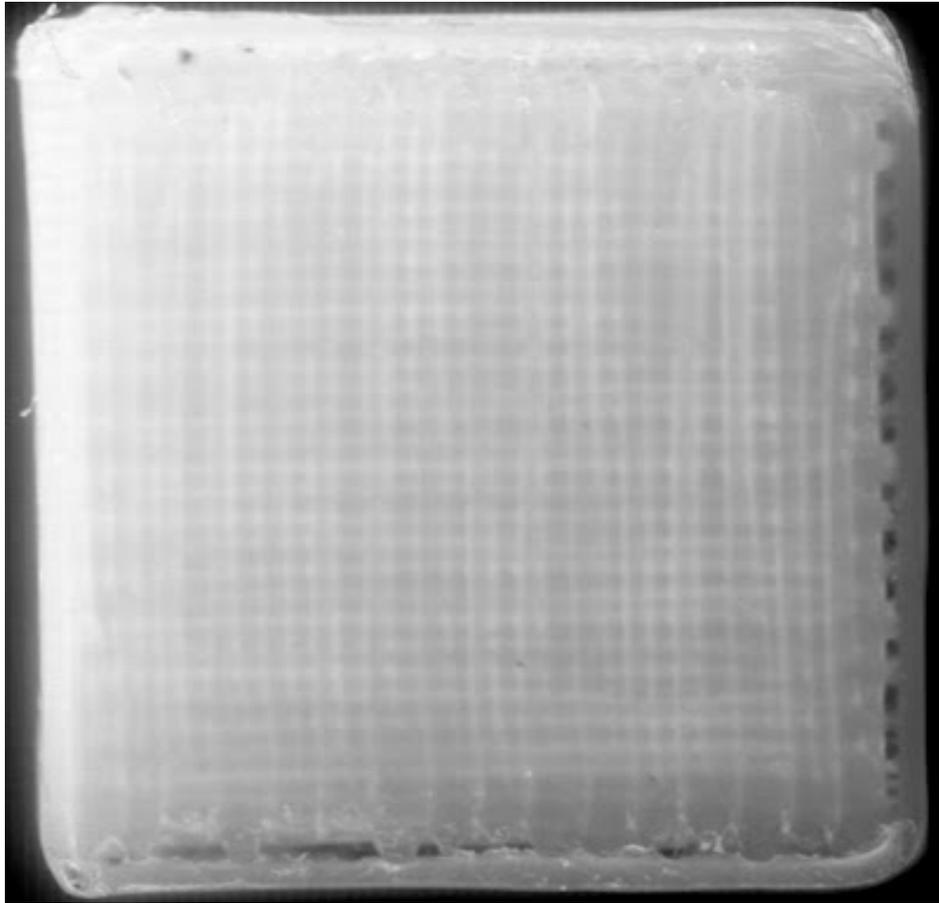
I think the variation is due to the fact that my extruder spindle is a bit off centre. This causes the torque to go up and down as it rotates, which causes the flexible drive cable to wind up and run down again. This causes speed variations despite the fact that the motor speed is well regulated. At some point I will get rid of the flexible drive.

I expect the fact that I am stretching the filament doesn't help with the corner cutting. I improved it a lot by slowing down the drawing of the outline to 4mm/s and leaving the infill at 16mm/s. Here is the result :-



Still not perfect, another thing to try would be to recognise that there is a minimum corner radius and make the nozzle follow an arc of that radius around the corner. At least that way it might be more uniform.

Here is a close up of the top face taken with a scanner:-



As it goes round the corner the filament has an external radius of about 1.5mm and an internal radius of 0.9mm. As it is 0.6mm wide that is probably not bad. You can also see that the zigzag infill sometimes ends a bit short of the edge, probably also due to corner cutting.

To get sharper corners I expect I need to use a nozzle with a smaller hole, so that the filament can be fine without having to be stretched, but that has the disadvantage of slowing down the extrusion rate for a given pressure.

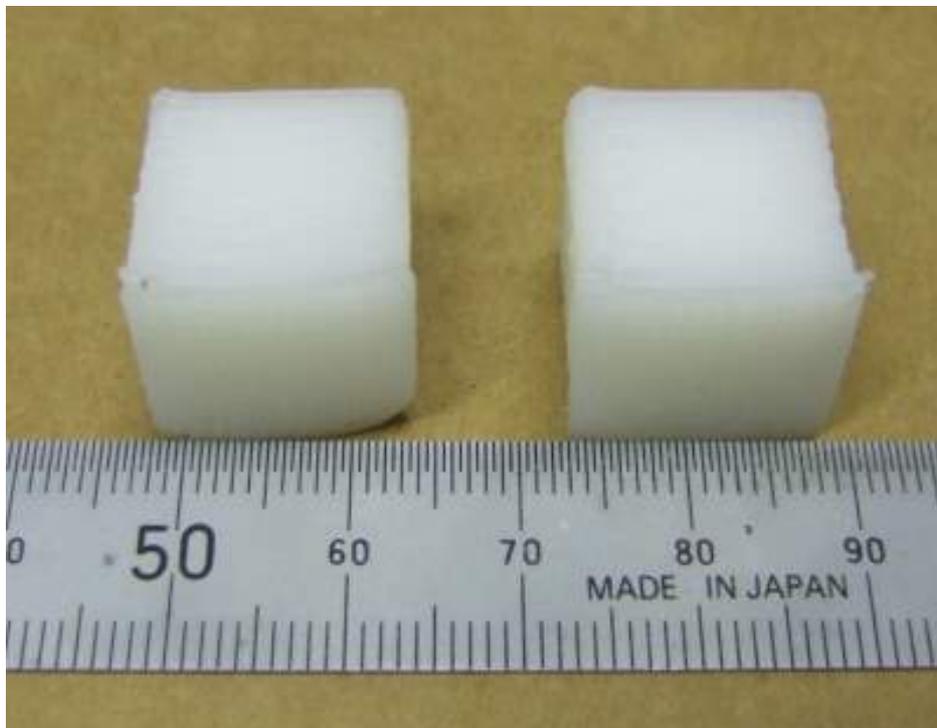
# To raft or not to raft?

Friday, 28th December 2007 by Nophead

When extruding HDPE onto foam board a raft needs to be laid down first to increase the anchorage at the corners to reduce curling. It becomes part of the object and has to be trimmed back to its outline with scissors or a knife. Now that I am extruding onto polypropylene cutting board I wondered if it was still necessary.

The temperature at which I lay down HDPE onto the cutting board is important. At 180°C it does not stick. At 200°C it sticks well but can be peeled off with the help of a penknife. Higher temperatures make it harder to remove and do more damage to the board.

Here are a couple of 15mm test cubes made directly onto the PP board without a raft :-



The one on the left had the first layer extruded at 200°C and subsequent layers at 240°C. As you can see it curled badly, particularly at one corner. The one on the right had its first layer extruded at 220°C. It looked promising but when I tried my standard warp test block the result was not good!



So it looks like the raft is here to stay. Here is an example :-



I lay down the raft at 4mm/s with a notional filament diameter of 1.1mm with the extruder head 1.3mm above the board. This is to get the filament as round as possible so that it doesn't form a solid weld. In actual fact, gravity causes it to slump to about 0.9mm high and spread to 1.3mm wide. The oval area calculation would give 1.34mm and a pitch of 1.3mm is sufficient to get adjacent filaments to stick together. My rationale for making the raft as thick as possible in one layer was to make it strong without taking too much time. It probably does not need to be as strong now that it binds to the PP.

I put the raft down at 200°C, then I do the first layer of the object at 240°C with the fan off to ensure it welds to the raft and then subsequent layers at 240°C with the fan on.

I calculate the amount the raft overlaps the object with this completely arbitrary function :-

```
def overlap(x):  
    return x + 10 + 10.0 * (x - 20) / 80
```

I halved the overlap when I went from foam board to polypropylene.

# Wear and tear

Friday, 28th December 2007 by Nophead

My extruder's heater went open circuit so I removed the heat shield to have a look at it. I have actually run it for many hours now and have extruded quite a lot of HDPE. I have about 200g of extruded test objects and scrap which represents about 13 hours operation. I only recently started saving my scrap so I must have extruded a lot more. The 2.5Kg reel of HDPE is noticeably smaller.

The heater has also run for a lot longer than the extruder has been extruding. I got fed up of waiting for it to warm up at the start of each run so my host software leaves it on. I keep meaning to put a timeout in the firmware to turn it off when there hasn't been any Ethernet messages for a while as I have left it on for long periods a few times.

The extruder is starting to show some signs of aging. The plastic shield which keeps the fan draft away from the nozzle looked like this when I made it :-



But now it looks like this :-



The nozzle itself now looks like this :-



The JBWeld that surrounds the heater wire has gone very dark and has several cracks in it. One of the heater connections broke off in a previous accident so I dug it out and joined a piece of copper wire by squeezing it tight and soldering it. There is now no sign of the solder which is why it has gone open circuit.

The black stuff which looks like bitumen must be slow cooked HDPE. I am surprised that long term heating to 240°C causes it to decompose. I don't know if the white surface on the shield is just due to its surface melting a bit or whether something boiled off the nozzle and condensed onto it or reacted with it.

Even the high temp insulation over the thermistor wires is starting to look a bit sad!

I also noticed that the steel wire that forms the flexible drive coupling is starting to break up. A couple of strands have snapped and there is a pile of black dust on top of the pump shell.



The heater connection should be easy to fix. I have a few planned improvements to make to the extruder but I will wait till parts wear out before replacing them with better ones to get the most use of it.

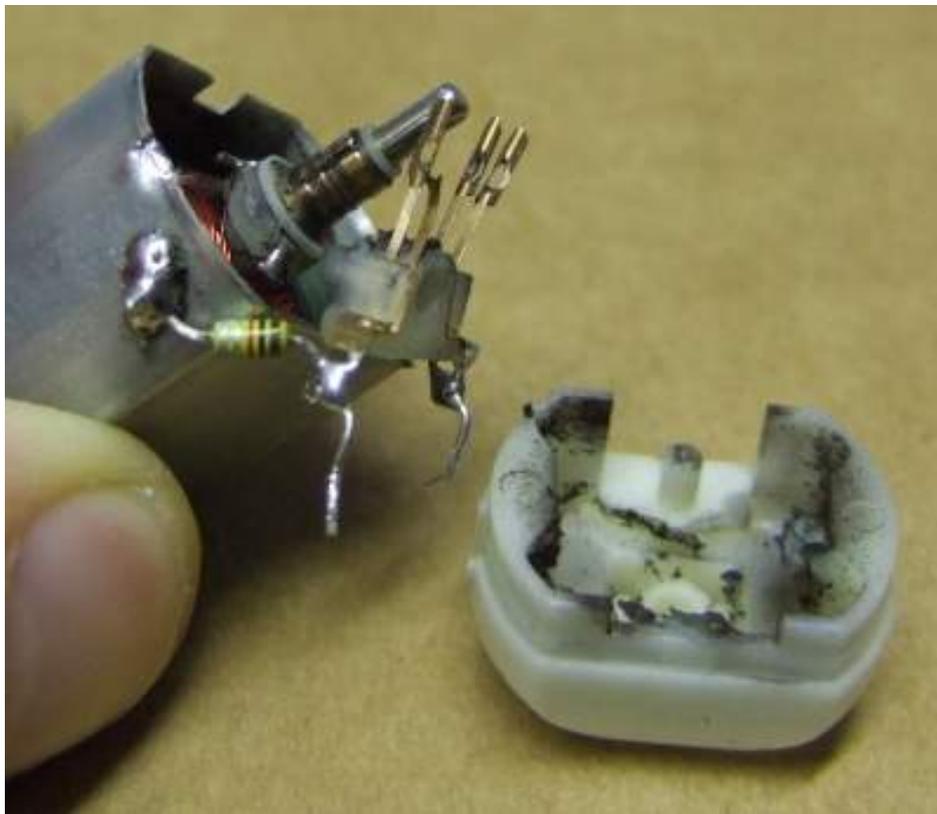
# Running repairs

Sunday, 30th December 2007 by Nophead

No sooner than I had fixed my heater, the extruder motor failed!

I bodged the heater connection by putting some more solder on it. It's not a permanent solution because the solder is molten while the heater is on so it slowly oxidizes away. The last time bodged it that way it lasted six months though. It really needs a crimped connection.

The GM3 motor failed by running slowly, getting very hot and drawing lots of current. It eventually caused the protected MOSFET that is driving it to shut down. Opening it up soon revealed how it had failed :-



It has two pairs of copper brushes. Three of them have holes worn right through and the fourth has broken off. Its stub was touching the wrong side of the commutator, causing a short.

More expensive motors have carbon blocks on the end of arms which can wear down a lot further before they fail. Bigger motors have spring loaded carbon rods. The gearbox shows no sign of wear so it is let down by the cheap motor.

This motor is not really up to the job of driving the extruder. It is being severely abused by running it from 12V PWM when it is only rated at 6V. I anticipated it would not last long and ordered a spare when I bought it. I fitted that and HydraRaptor is up and running again. Curiously the second

motor seems a lot quieter than the first.

At some point I think I will upgrade to a stepper motor. They are more expensive but, as long as you don't load the bearings, they last virtually forever. In the long run they probably work out cheaper and I can also dispense with the shaft encoder and the interference suppressor.

# If it's not one thing it's another!

Wednesday, 2nd January 2008 by Nophead

The third post in a row about my extruder breaking, not a good start to the year!

Now that I am making solid test shapes rather than hollow ones the extruder is working a lot harder and all it seems to do is break down. The drive cable started to disintegrate this afternoon, I could hear the strands breaking :-



It was still limping on however when this happened :-



The brass nozzle started to come out of the PTFE heat barrier. This was ironic because it was only yesterday that I said I had not had this problem in a forum discussion. Others have had it happen and the collective wisdom is to use a pipe clip round the end of the PTFE to secure it.

And the JB Weld which insulates the heater wire has turned to dust :-



So some rebuilding to do!

# Extruder postmortem

Sunday, 27th January 2008 by Nophead

So my extruder died at the beginning of the month. I have been busy with other things so I have only just got round to thinking about rebuilding it. Here is a list of things that failed :-

I got my extruder working in mid August. At the end of September it ejected its PTFE barrel from the clamp, breaking the heater wires. This is a common problem and stems from the fact that PTFE has the lowest coefficient of friction of any known solid material. I tightened it further and it didn't slip out again. However, when I came to dismantling it I noticed that the end that was in the clamp has been compressed by about 0.3mm. The 3.2mm drill that I made the hole with is now quite a tight fit so the hole may have shrunk slightly. I will drill it out to 3.3mm because some of my 3mm HDPE filament is slightly more than 3.2mm where it is a bit oval.

One curious thing is that it now looks to have a thread in the entry hole.

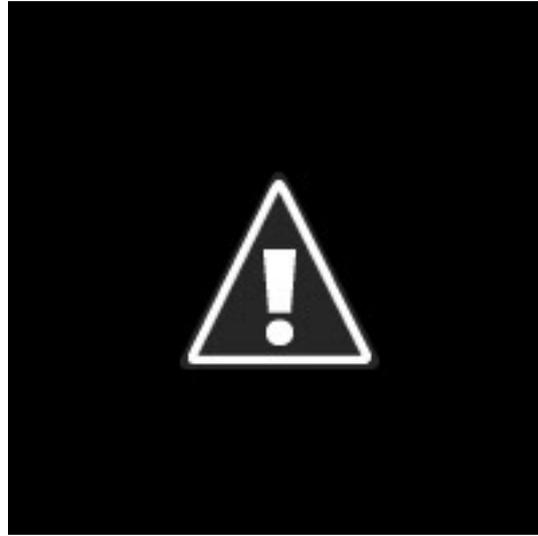


I am struggling to explain this. The only way I can think it may have happened is as follows :-

The filament has a thread cut into one side by the drive screw. Before I added my feed spool the filament used to rotate as it went through the extruder and had a thread cut all the way round.

Perhaps it transferred its thread to the PTFE, which is quite soft.

The final failure mode was the nozzle jumping a couple of threads and leaking molten HDPE. It rammed the nozzle through the object being made and damaged the bed underneath.



The bottom end of the PTFE barrel has swollen by about 0.3mm. PTFE is known to creep, i.e. when subjected to a prolonged force it very slowly flows. It has no memory so it does not spring back when the pressure is removed. I think this is why the top of the barrel shrank and the bottom expanded. There is a lot of pressure in the barrel and it is close to PTFE's maximum operating temperature. PTFE melts at 327°C but it starts to degrade at 260°C. I have been running at 240°C which is a bit too close for comfort.

My barrel, at 12mm, is smaller than the current recommendation which is 16mm. This may have contributed to the failure.

The recommended solution is to fit a pipe clip, but I didn't have one small enough, so I pressed a short section of 15mm OD pipe over the end, which is a tight fit. It had the desired effect. When I first made the barrel the thread was a snug fit. When I dismantled it I noticed it had become quite sloppy. With the ring of metal in place it is now a tight fit. I will use some plumber's PTFE tape to seal it as well.



The other thing that was on the point of failing was the flexible drive shaft. Strands started breaking and the more that broke the more it flexed, so it was a kind of avalanche effect. I estimate that the shaft had rotated about 100,000 times so the flexing backwards and forwards must have caused metal fatigue. I probably have the most mileage on this part of anybody so far so it could be a sign of a design flaw. There are a couple of problems with my implementation which certainly won't have helped.

The first is that I used some 2.5mm cable I had to hand rather than the 3mm recommended. It doesn't seem like a big difference but I think the rotary strength is at least a cube law which would make my cable roughly half as strong. It was left over from a garage door installation but I don't think I have any worries there as 100,000 flexes is about 75 years use!

The other contributory factor is that the bearing lands on my drive shaft are a little bit eccentric. This stems from the fact that my watchmaker's lathe is not really big enough for this work. Fundamentally the hole through the headstock is not big enough to take the 5mm threaded rod.

Each time the shaft rotates it opens and closes the pump halves a little. This makes a big torque variation over a revolution because of the strong springs holding it closed. That caused the cable to wind up and unwind a little each revolution. It actually modulated the filament width and gave the objects a basket weave appearance. Here is a good example :-



I bought some new parts from [www.bitsfrombytes.com](http://www.bitsfrombytes.com), which wasn't an option when I first made the extruder.



That will allow me to give the flexible drive a fair test. If it proves to be unreliable then I will switch to direct drive. I found out from the core team that it is not required for any of the polymers currently used, only things like Field's metal.

Another thing that was starting to fail was the J-B Weld holding the heater wire to the nozzle. It is supposed to be rated to 315°C but it had started to crumble with my extruder running at 240C. The other problem I had with my J-B Weld is that it does not cure in the specified time at room temperature. I have to bake it to make it strong. I emailed J-B Weld but got no response apart from an automated reply.

David commented on my last post suggesting Thermosteel ,which is good for 1300C,so I will try that next. A couple of the core team use BBQ paint which handles 600°C so I will try that as well.

# Nuts

Saturday, 2nd February 2008 by Nophead

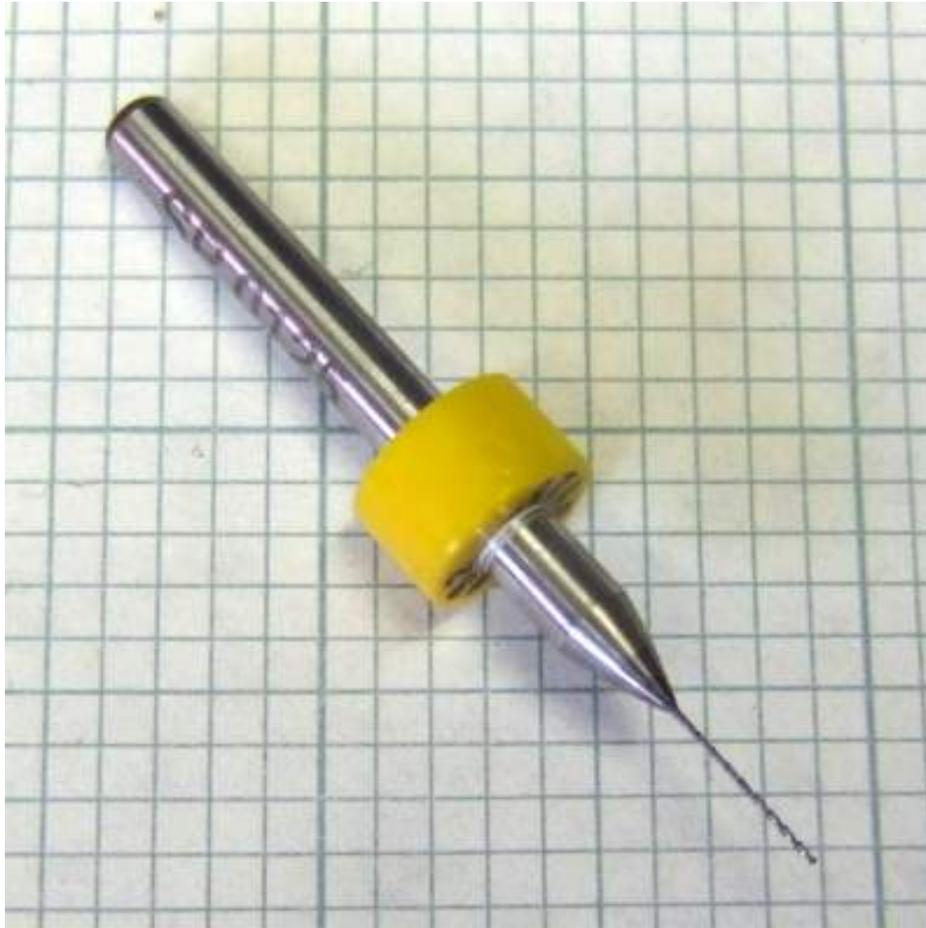
Since my first attempt at making the RepRap extruder the design has moved on to use a brass acorn nut as the nozzle. It has the advantages of making the extruder easier to fabricate, allows the aperture size to be changed by swapping nuts and allows blockages to be cleared. I have to say that I never experienced a blockage with my single piece nozzle, but I can see how it could easily happen if a bit of dirt bigger than the aperture gets into the barrel.

Unfortunately brass acorn nuts, otherwise known as dome nuts and cap nuts, are expensive and hard to get hold of. I got a couple of un-drilled ones from [BitsFromBytes](#).



My plan was to start with the smallest hole I could drill and expand upwards to see what effect it had and then drill the other to the size I found to be the best. Stupidly, I overestimated how thick the dome was and put a centre drill right through the first one. So now I have one with a 0.3mm hole and the other is about 1.1mm.

This is the 0.3mm bit I used :-



If you use a drill or a drill press it is easy to snap drill bits this small but it is actually very easy to drill 0.3mm holes with a lathe. I spin the nut in the chuck and hold the drill in my fingers. I drill from the inside of the dome. The drill finds its own centre and then I apply light pressure. I expect the same could be done by spinning the nut in a drill chuck.

The RepRap design for the heater barrel is just a flat ended threaded brass tube made from an M6 bolt. This is easy to make but not the ideal shape. Brass acorn nuts seem to be machined from a solid piece of brass. The internal thread is made by drilling and tapping. Because it is a blind hole that means that the thread does not go all the way to the end. If you screw a flat ended barrel into it then it stops short of the end, leaving a void that will fill with molten plastic as can be seen here. Molten thermoplastics compress under pressure, so ideally the amount of molten plastic in the extruder should be kept as small as possible to make the start stop response as fast as possible.

I decided to sacrifice my over drilled nut to find out the inside profile by cross sectioning it :-



Not surprisingly, the inside profile matches a 5mm drill as that is the correct size for tapping an M5x1 thread.



This is how far a flat ended barrel can enter :-



This is my attempt to match the profile :-



And this is the improved fit :-



The chamfer at the end is not quite right. My DeWalt bits have a  $110^\circ$  angle but the standard appears to be  $118^\circ$ .

I decided to take a look at steel acorn nuts :-



These are a completely different animal. Rather than being machined out of one piece they consist of a nut with a dome pressed into it.



They have some advantages and disadvantages : -

- They are cheaper and more commonly available.
- They are smaller so less thermal mass.
- The dome is much thinner, about 0.4mm rather than 1mm, so it is easier to get a short hole.
- Steel has a much lower thermal conductivity than brass so plastic may cool down in the nozzle.
- Steel has a different thermal expansion rate than brass. Fortunately it is less so it should get tighter as the extruder warms up.
- The steel dome might spring out under the pressure of extrusion.
- The flat ended heater barrel goes in further but leaves voids at the side.



These are just the nuts I have managed to buy. I have no idea how much they vary from one supplier to another.

The heat insulator in the picture above is an experimental one turned from a bar of soapstone.

# Bottoming

Sunday, 3rd February 2008 by Nophead

As well as repairing my extruder I aimed to bring it closer to the latest RepRap design. The machined heater barrel has been replaced by a drilled out brass bolt. Partly out of laziness, and partly out of a lack of confidence in my skill with a lathe, I bought a ready made barrel from BitsFromBytes.



I was surprised to find it came with a modification that I had blogged when I made my first nozzle. That was to turn down the end that fits into the PTFE holder to get round the fact that I didn't have a bottoming tap to make the thread go right to the end of the hole in the PTFE. Ironically, I had bought a set of taps which included a bottoming one in the meantime. Well at least I thought I had :-



The tap on the left is the one from my cheap set of taps which only has one for each thread. The boxed set are the new ones that I bought with a taper, second and bottom tap. The single tap

seems to correspond to the second tap, which makes sense for a compromise. The thing I don't understand is why the bottom tap still has a point and some taper. I was expecting it to be straight with a flat end, so I made it thus with a grinder :-



To try it out, I made a test thread in a scrap of PTFE and cross sectioned it :-



As you can see the flat end of the heater barrel butts up nicely to the end of the thread in the PTFE. I think it is important not to have a void here as it will fill with molten plastic which will freeze when the heater is switched off. It might then be difficult to melt it again as it is insulated from the heater.

The end of the barrel that is turned down is then a pretty good fit for the acorn nut, although a simpler solution is probably to bottom the thread in the nut and the PTFE and then go back to a plain heater barrel.

## Tough as steel, my a...

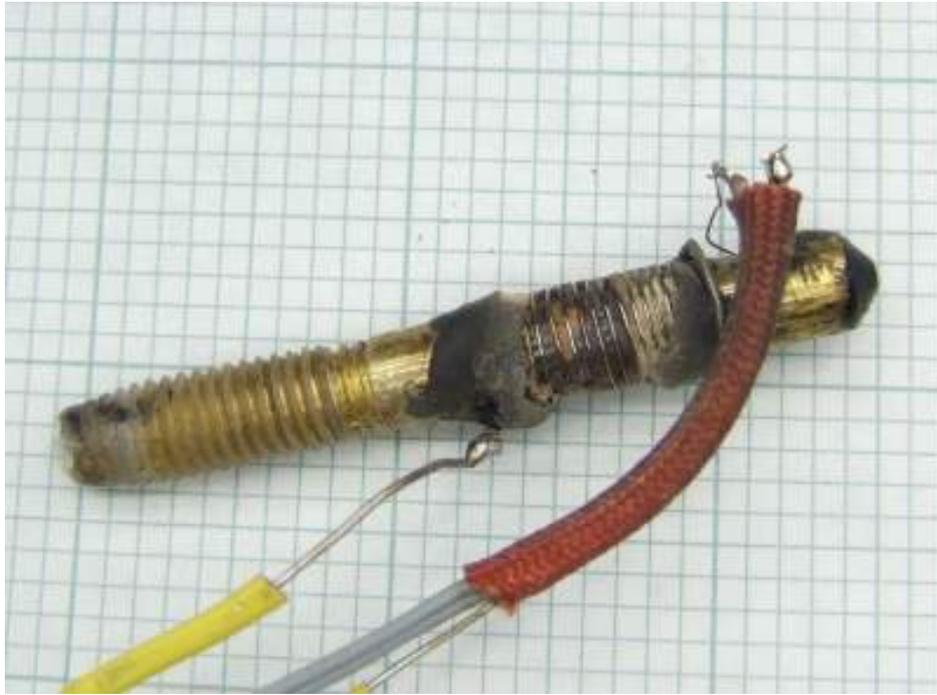
Monday, 11th February 2008 by Nophead

I had originally intended to rebuild my extruder with the barrel I bought from [BitsFromBytes](#) but I ran into a compatibility problem with the nichrome wire I am using. My wire, as well as being un-insulated, is a bit lower resistance than the recommended stuff, which I can't buy in the UK. I need about 300 mm rather than 200 mm to get the required resistance.

Going from a 6 mm barrel to an M6 threaded barrel means that I can only wind it with the pitch of the thread (1 mm) and the diameter is reduced, so there isn't enough room to accommodate 300 mm. A friend suggested using a finer thread which seemed like a plan. I have an M6 x 0.75 tap and die so I thought I would use that. Unfortunately finer pitch means shallower, so I would need a 5.25 mm drill bit which I don't have and I thought it was probably a bad idea to use a shallower thread in the PTFE. So in the end I made a new barrel with a thread on each end and an un-threaded section for the heater :-



I used J-B Weld for my last heater but it did not stand up to the heat very well. The bit near the thermistor, which I know was at 240C, and the ends of the heater remained strong, but the rest turned to a light brown dust with a harder darker skin over it. It was still functioning as a heater until I touched it at which point it started to flake away.



On the packet it states "J-B Weld maximum temperature is 600°F" which is 315°C. I know the heating element is going to be a bit hotter than the barrel, particularly when I was extruding with a fan on, because of the temperature drop across the thermal resistance of the J-B Weld. I doubt that it got to 315°C though. I emailed J-B Weld about this but I didn't get any reply other than an auto acknowledgment. Looking at their [website](#) I see the following "withstands temperatures up to 500°F" which is only 260°C so no wonder it failed.

The RepRap [instructions](#) suggest using Dulux Spraykote BBQ paint as a substitute for J-B Weld under the heading "But They Don't Sell JB Weld Here". Ironically they only seem to sell that in New Zealand so I got a local BBQ paint.



It turned out to be quite nasty stuff. Probably not a good idea using it in doors but it is too cold to do it outside at the moment. It went on easy enough but the RepRap instructions suggest three coats under the wire and four over it.



There are no instructions on the paint about drying times and re-coating. Impatiently I dried it with a heat gun, as it is rated to 450°C, but it blistered. I should probably have used a hair dryer and / or been a bit more patient. I apologise for the rubbish photo but you can see the size of the blisters.



I tried turning them down with the lathe but the paint just flaked off so I was back to square one.

I then thought I would give ThermoSteel a try. Supposedly it is a steel filled water based epoxy paste similar to J-B Weld but rated to 1318°C, although I don't know how you can have water based epoxy. I read somewhere else it was a ceramic paste which makes a bit more sense to me although I am not a chemist.



My plan was to put down a thin layer and then machine it flat with the lathe, wind the heater and cover it with a thicker layer, a technique I used successfully with the J-B Weld. It does say it is machinable.

When mixed up it resembles wall paper paste with iron filings in it. It was impossible to spread thinly, I had to dab it on to get it to stick.



I let it set over night and then as it says it gets stronger when heated (although it does not say to what temperature), I heated it up to gas mark 9 which is 260°C at the rate our oven warms up and then let it cool down at the rate the oven cools down when switched off. When it came out it looked like this :-



It looked a bit fragile so I scraped it with my fingernail and it came off in much the same way as the J-B Weld did!



So not getting very far with making a new heater. I have no idea why my ThermoSteel is a weak crumbly substance instead of something resembling steel. Should I have heated it a lot more? Have I been sold a small pot of wallpaper paste with Iron fillings in for £12.75?

I am not sure what to do now, perhaps try the BBQ paint again, use J-B Weld as I know it at least

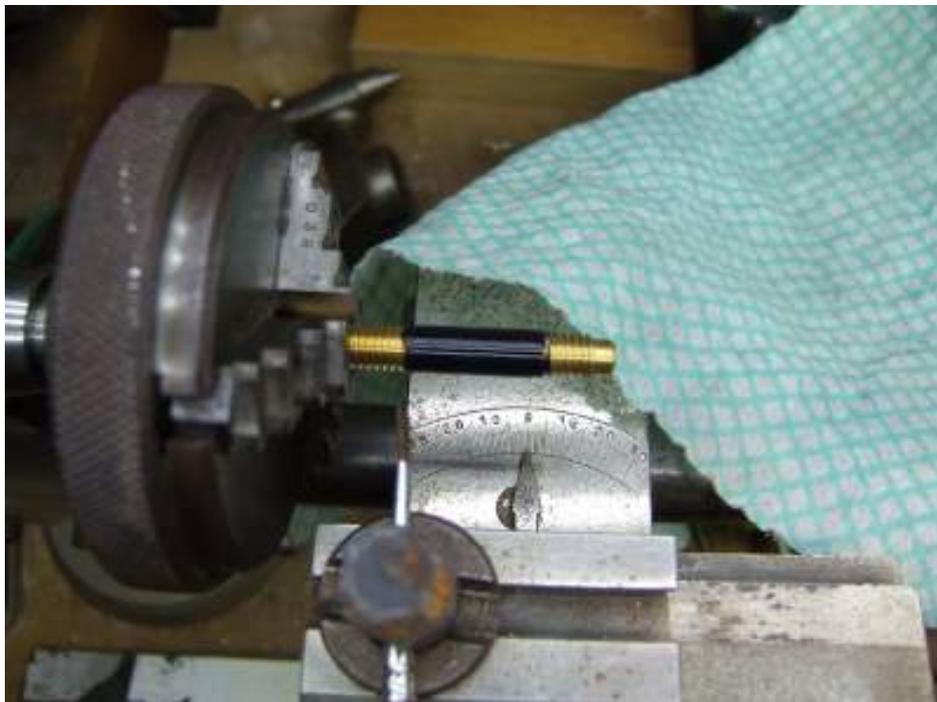
works for several months or make an induction heater.

# Back to square one

Saturday, 16th February 2008 by Nophead

I moved on from J-B Weld as a means of making a heater because it does not handle the high temperatures I have been using for HDPE. I completely failed with Thermosteel so I decided to have another go with BBQ paint. It seems that I must have the wrong sort of paint because despite helpful advice from Vik Olliver and Forrest Higgs, after a week of trying I can not get it to work.

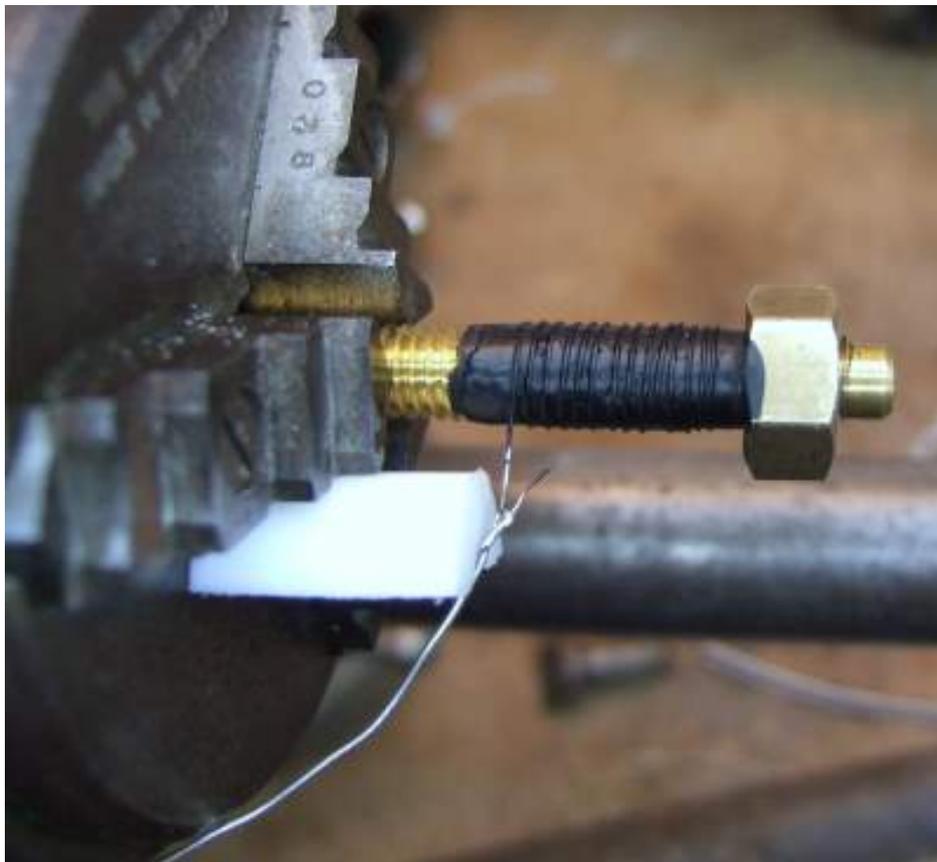
After many attempts the final method I used was to put down three coats of paint using a paint brush in my lathe. Each layer has to be allowed to dry for many hours and then baked with a heat gun. If I apply heat too soon then it blisters. If I don't apply heat then the next coat simply dissolves the coat underneath. The paint has a lot of very volatile solvent in it.



Once I had three coats, I baked it in the oven on full blast (gas mark 9+) to make it hard enough to take the wire. I anchored one end of the wire with a nut that has a small hole drilled through it and attached a weight to the other end to keep it taught while winding.

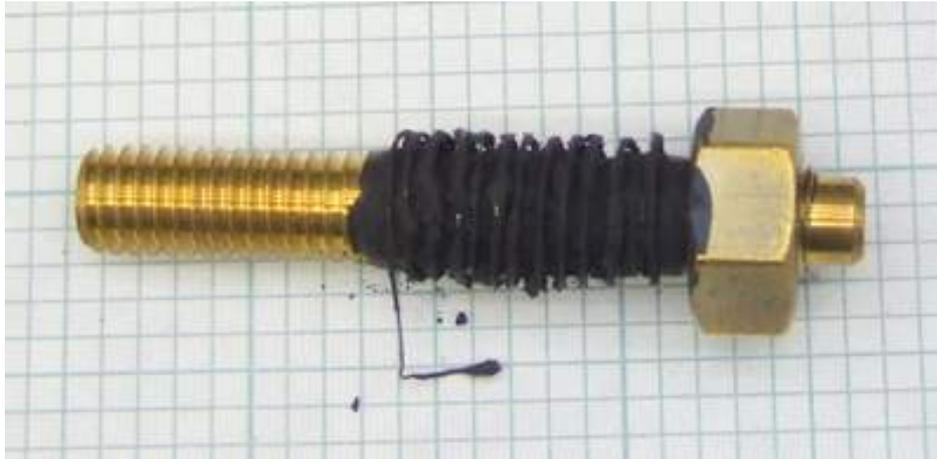


To keep the wire in place while I painted over it I tied it to a piece of copper wire wrapped round the back of the chuck. To keep the tension in the right direction I used a piece of PTFE left over from a previous experiment to support it. It was an ideal shape and could stand the heat from the heat gun.



The picture above is after one coat of paint. When the paint was applied it was thick enough to

completely cover the wire but when it dries it is very thin. I put five more coats on and baked it in the oven. I was somewhat disappointed when it came out like this :-



The paint resembles soot and has no strength to it at all. I can scrape it away with my finger, like I could with the Thermosteel.

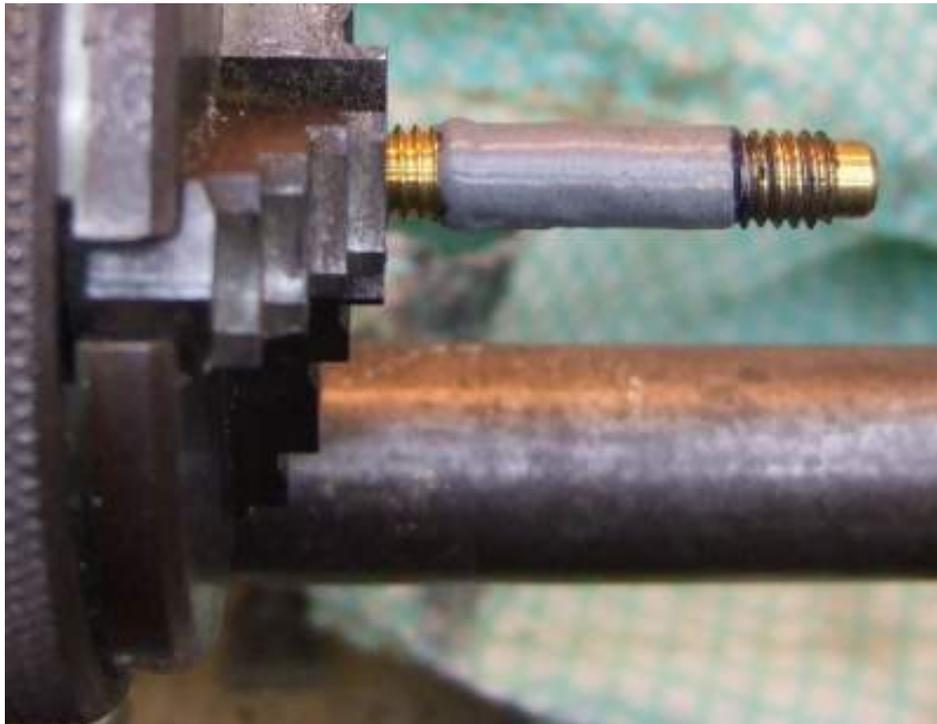
Time to step back from this and think again. It is crazy trying to use high temperature paint as a high temperature adhesive. Some makes of paint may work, but you can't complain when other makes don't. I think it makes a lot more sense to use something designed to do the job such as Cerastil H-115. I will order some on Monday. In the meantime I will go back to J-B Weld because it is easy to use and will last for months if I keep the temperature down.

# J-B Weld Heater

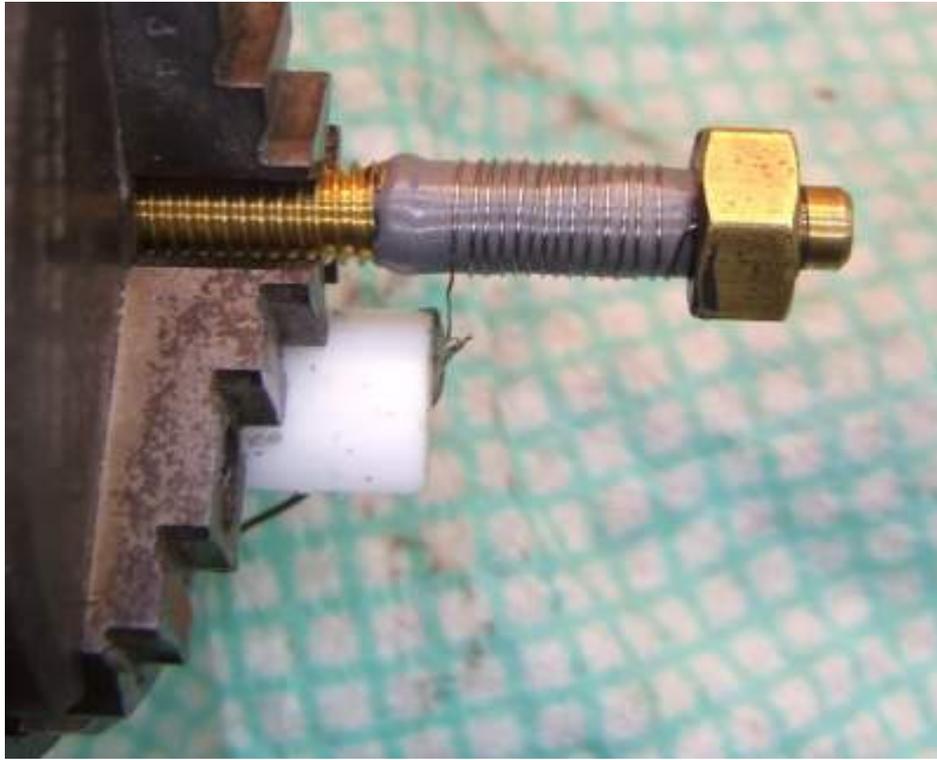
Tuesday, 19th February 2008 by Nophead

I ordered some Cerastil H-115 high temperature ceramic glue today but it will not arrive for a few weeks so I made another heater with J-B Weld. It is much quicker and easier than using BBQ paint.

I spread a thin layer on the barrel to insulate it and left it for 6 hours to set. Last time I used a thicker layer and turned it down but this time I just spread it very thinly with a spatula while hand rotating the lathe.



Next I wound the nichrome using a nut with a small hole drilled in it to anchor the start. I anchored the end using a piece of copper wire tied to it and pulled over a support round the back of the chuck. I expect this could be done with a drill chuck if you don't have a lathe.



I then added a second, thicker, layer of J-B Weld and left it over night to set.



Finally I slowly heated it up to 200°C in an oven to cure it.



I haven't tested it yet, apart from checking it for opens and shorts but it is pretty much the same method I used first time around: [hydraraptor.blogspot.com/2007/07/hotting-up](http://hydraraptor.blogspot.com/2007/07/hotting-up)

# Nutty Nozzle

Wednesday, 20th February 2008 by Nophead

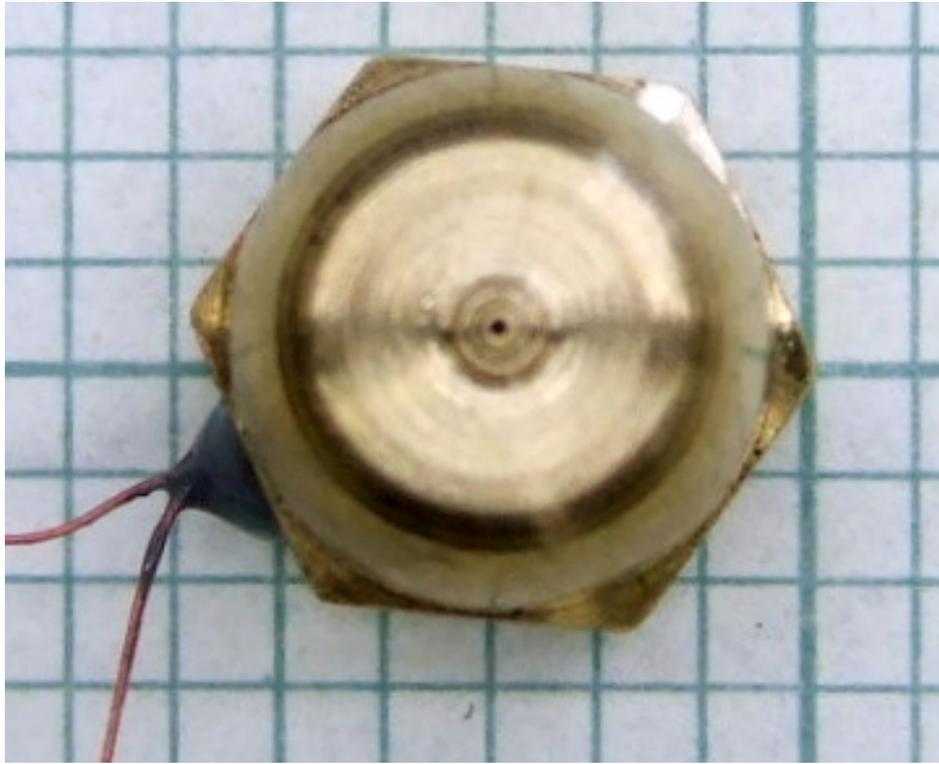
My old extruder nozzle was made from a solid brass rod with a 0.5mm hole in the end.



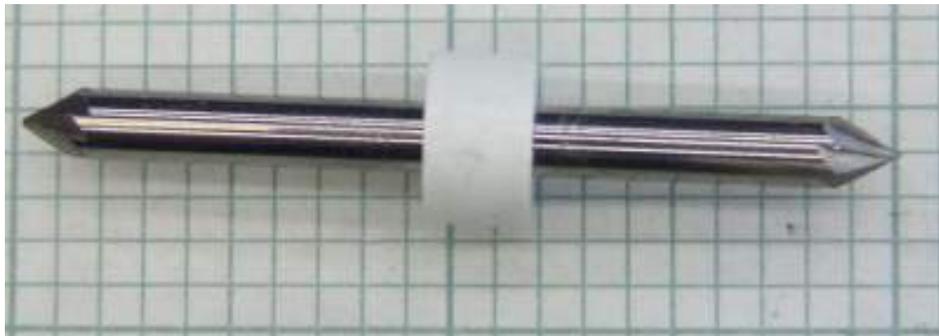
It was drilled 3.2mm from the other end to accept the filament. The problem was gauging how far to drill from the back. Ideally the hole in the end should be as short as possible to provide less resistance to the filament flow. Drilling too far would write it off so I erred on the side of caution.

I suspected it was a bit on the long side as I got more die swell than I was expecting. Since it is now scrap I sectioned it to find out exactly how long the hole was. It turns out it was about 0.6mm.

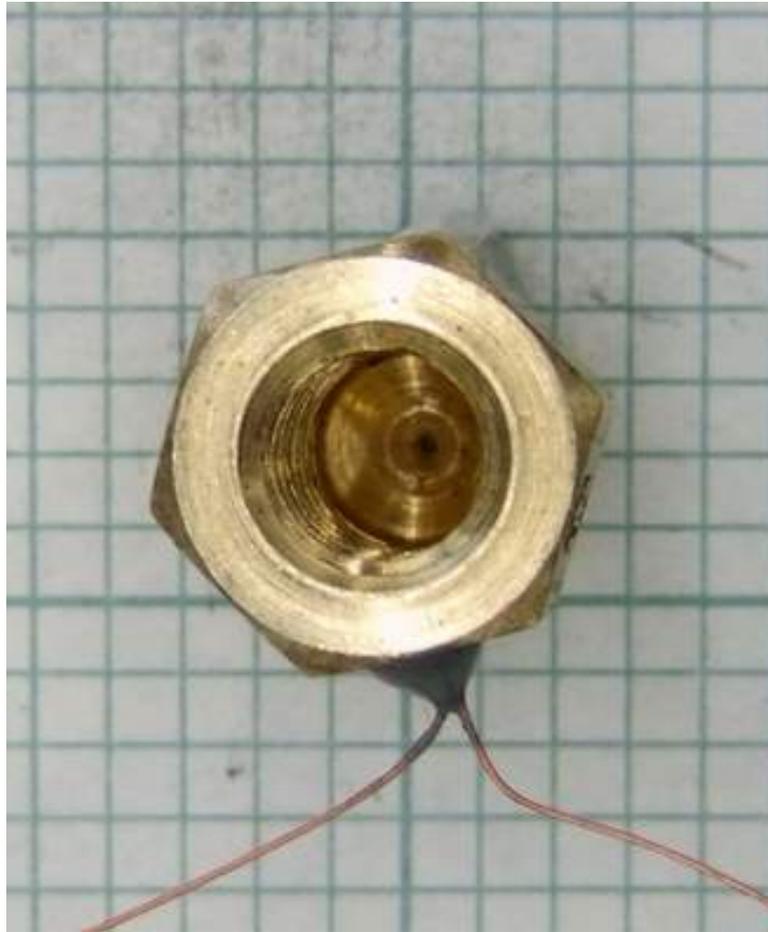
The latest RepRap design uses an acorn nut which gives much better access to the back of the hole. I used the smallest drill I have, which is 0.3mm, to start with, I might open it up later.



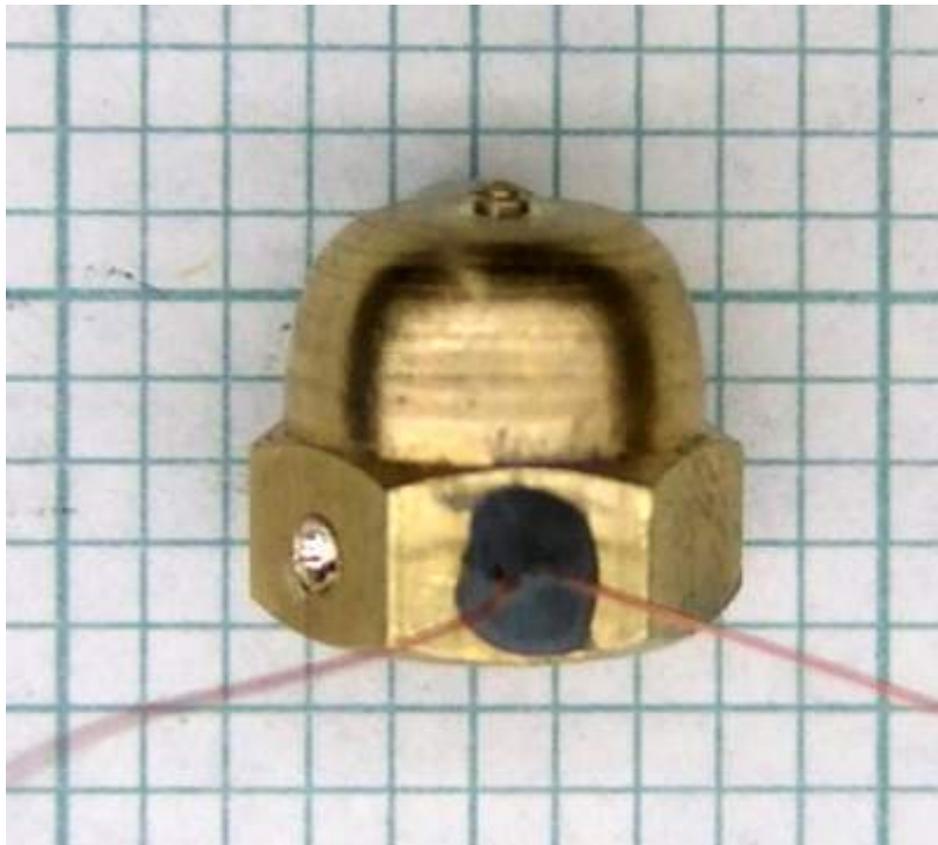
The dome of a brass acorn nut is quite thick so I opened the hole out from the back using a conical milling bit that I bought for PCB track isolation milling.



The point is actually about 0.3mm so I was able to countersink the hole from the back until the point came through. That means the rim of the hole is very thin indeed and there is a double taper leading to it. The first is created by the drill that made the thread hole in the acorn nut and then a shallower taper made by my mill bit. It will be interesting to see what flow rate and die swell I achieve with this close to ideal shaped aperture.



I turned down the front of the nozzle to a point to give some clearance to the work piece as suggested by Vik Olliver somewhere I can't find now.



The extra hole on the face next to the thermistor is to allow me to introduce a thermocouple during calibration.

# A riveting read

Sunday, 24th February 2008 by Nophead

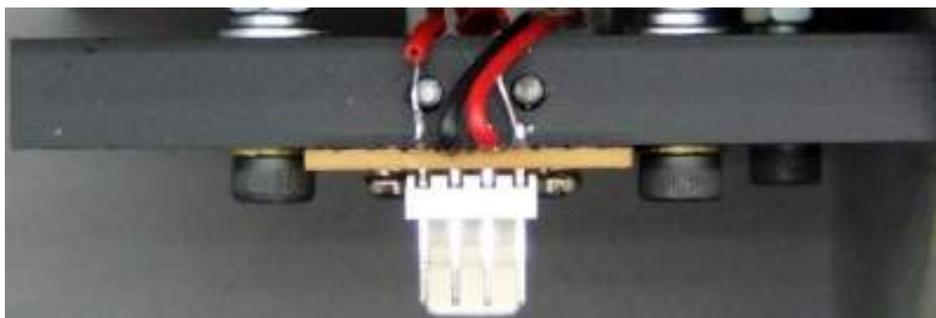
A recent modification to the RepRap extruder is the addition of two 3mm pins through the clamp and the PTFE insulator to prevent the PTFE slipping out. My PTFE tube is only 12mm diameter compared to the current design which is 16mm so 3mm pins are a bit too big for it. Instead I used some shafts from pop head rivets which are about 2.3 mm.



I drilled the holes 2.2mm to make them a snug fit.



Here are the pins installed through the clamp after being cut to length and rounded of with a grinder:-



# Thermal thoughts

Tuesday, 26th February 2008 by Nophead

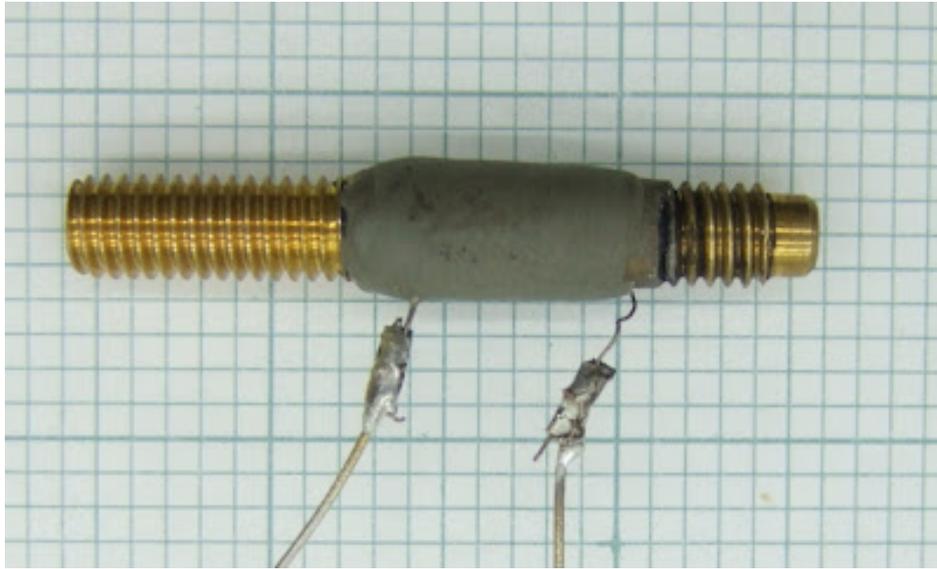
I attached the wires of my new heater with some small crimps that I cut from connector pins like this:-



to just leave the crimp part :-



I also soldered them with lead free solder which melts at about 220°C rather than the tin lead solder that I used last time, which melts at 183°C. It could do with being higher still so I might see if I can buy some high temperature solder (301°C) for the next one I make.



Rather than insulate with the recommended heat shrink sleeving, which is only rated for 125°C, I used some high temperature woven sleeving. Even that seems to discolour at 240°C. PTFE sleeving might be better.



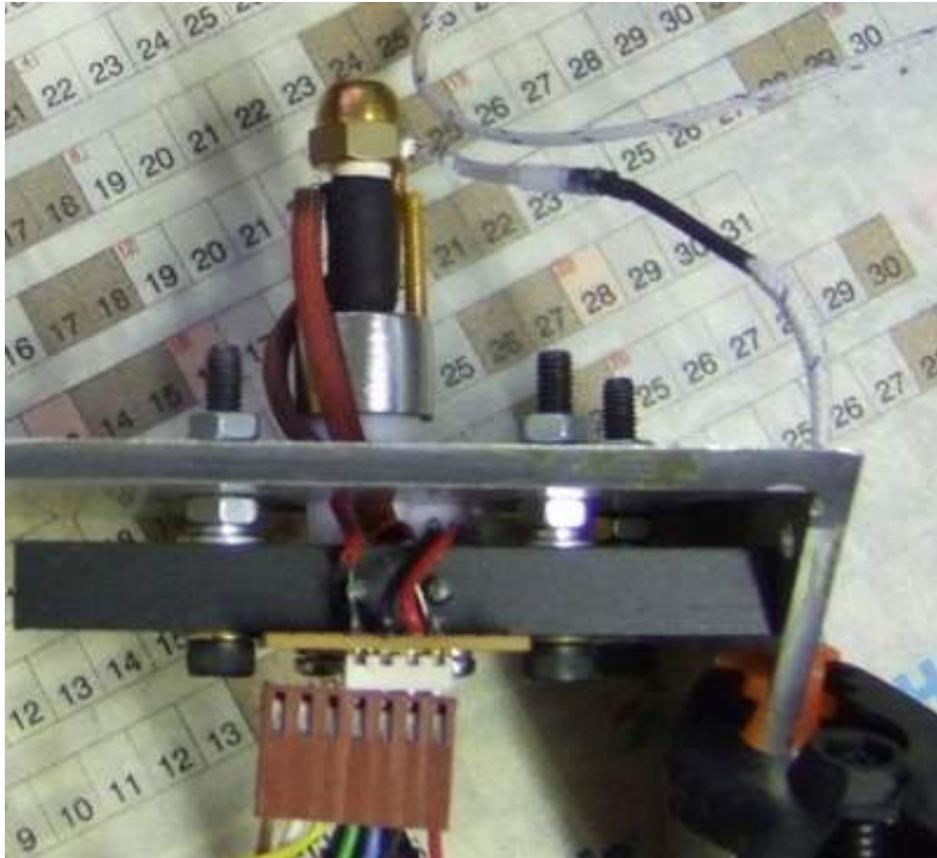
I pushed the wires from the thermistor into a two pin connector so that I can easily remove the nozzle.

I had to make a new mounting bracket because when I added the pipe around the PTFE insulator to stop it expanding it made it too big to go through the hole in my previous bracket, which also doubles as my spindle mount when milling.

The bit of aluminium box section I cut it from has been waiting for a new life since it appeared in a

prototype electronic photo booth on Tomorrow's World in the early nineties.

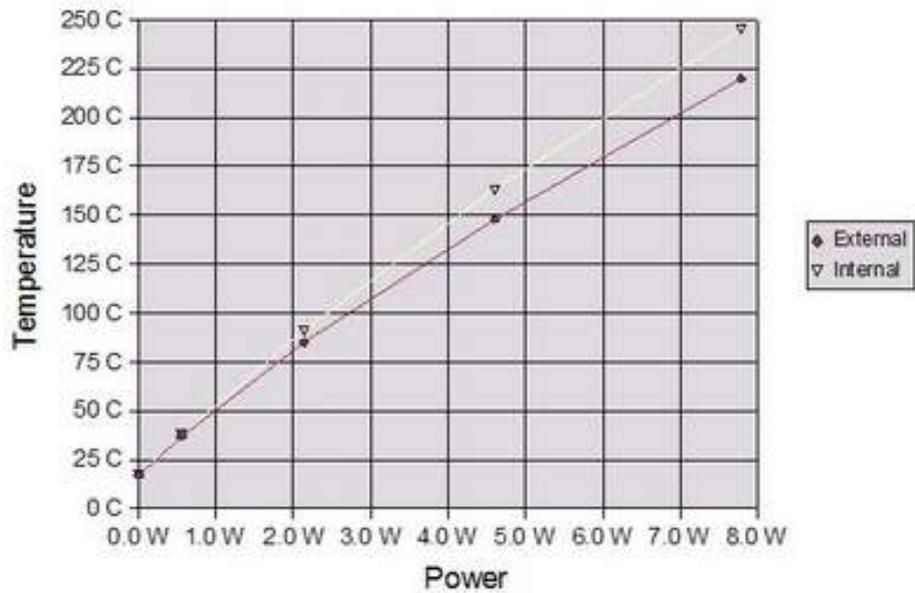
I calibrated the thermistor by putting a thermocouple into a second hole in the nozzle with some silicon grease. I also put a second thermocouple inside the barrel. I then put a range of voltages across the heater and waited for it to reach thermal equilibrium before reading the temperatures and the resistance of the thermistor.



Notice how dark the J-B Weld has gone when briefly heated to 240°C.

I made the new heater resistance 7.1 compared to 8.6 last time because I guessed the acorn nut nozzle would have a larger surface area and hence greater heat loss. In fact it has a remarkably similar temperature power curve to my last nozzle.

## Temperature v Power



Note that the difference between the internal and external temperatures is as much as 25°C. The PTFE tape I used to seal the nozzle may not be helping here. I also measured the outside temperature of the J-B Weld using an IR thermometer which read 242°C when the inside was 245°C and the nozzle was 220°C.

After calibrating the thermistor it seems to track the thermocouple within about 5°C.

# Coming back together at last

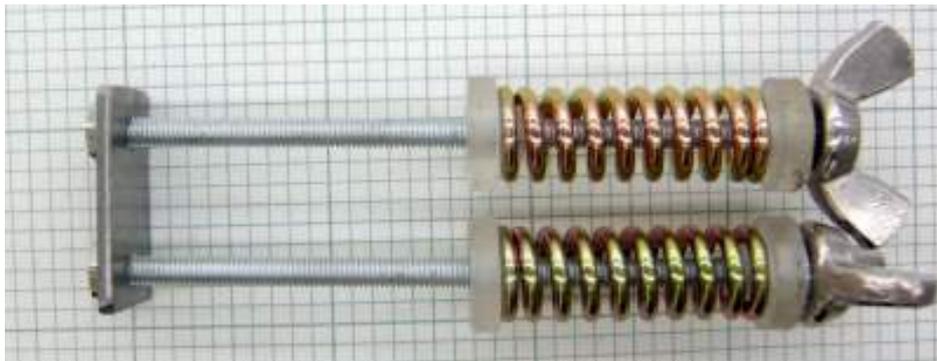
Thursday, 28th February 2008 by Nophead

One of the things that irritated me about the extruder was the time it took to open the pump and close it again. To make it slightly less fiddly I replaced the lock nuts with a pair of threaded steel plates :-

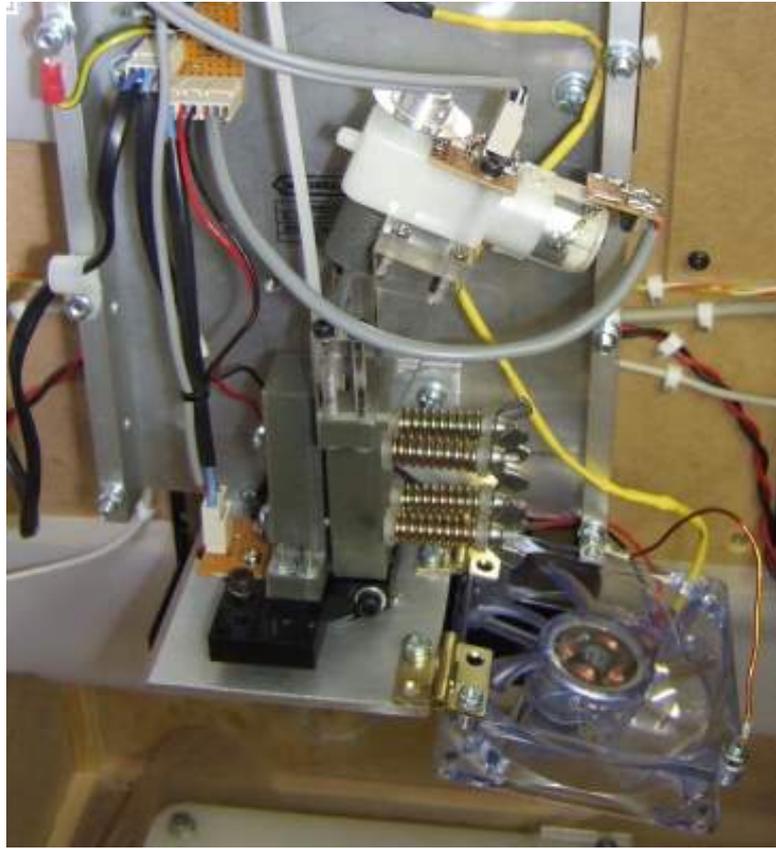


I used Forrest's recipe for cooling fluid while drilling these. It worked a treat, I had no idea you needed cooling when drilling steel to prevent the drill from being burnt.

The springs I used first time around that came from an old CD player weren't quite strong enough but I found some better ones in the hinges of an A3 scanner I dismantled recently. Six of these held the lid open.



Here they are installed on the machine :-



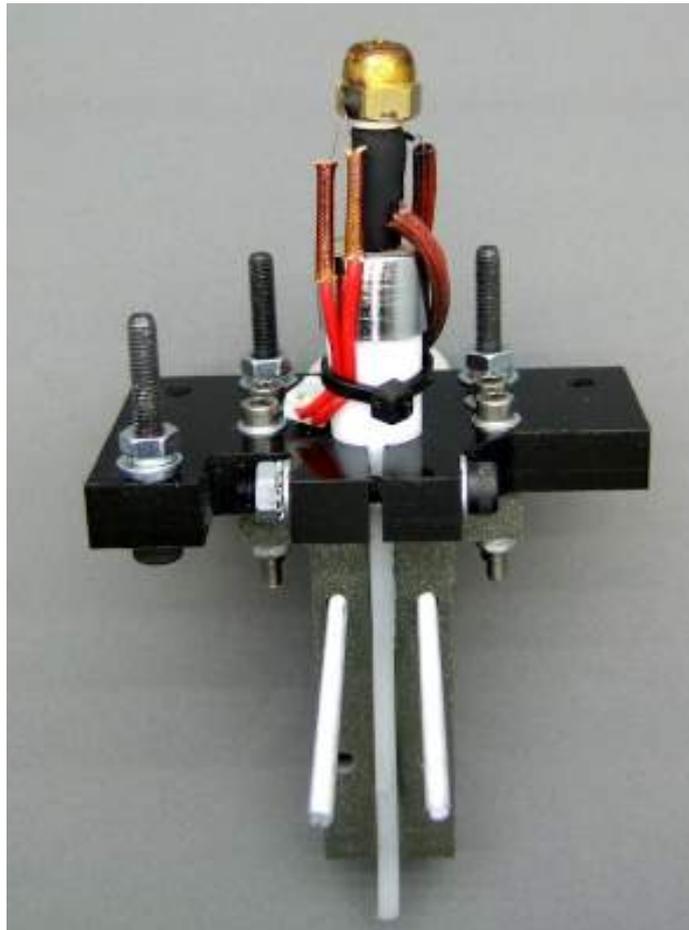
I should be extruding again tomorrow!

# Too much pressure?

Friday, 29th February 2008 by Nophead

Well my rebuilt extruder didn't last long enough to even make a raft!

I calibrated the Z origin yesterday but when I started extruding today the nozzle ploughed into the polypropylene bed. Thinking I had made some mistake I calibrated it again and it did the same thing. The PTFE barrel can no longer slip in the clamp because it is pinned. The heater barrel can not slip out of its thread because I have a metal ring around the PTFE to stop it swelling. What seems to have happened is that the PTFE barrel has elongated.



It has also bent somewhat. The last PTFE barrel did not elongate significantly but it did swell. I can only think that because I have reduced the nozzle aperture from 0.5mm to 0.3mm the pressure has increased. I didn't notice much change in the motor current though.

I am not sure what to do now. I could make a thicker PTFE barrel but I will have to make a new clamp, which means converting my machine back to a milling machine, or I could drill the hole out to 0.5mm.

A 0.5mm hole gave me ~1.2mm filament which I stretched to 0.5mm. The 0.3mm hole gave me 0.77mm filament at the same extrusion volume rate. It still needed stretching to meet my 0.5mm

target. Also it has the disadvantage that the maximum size I can extrude without stretching is now 0.77mm rather than 1.2mm. I didn't get chance to find out what effect less stretching had if any.

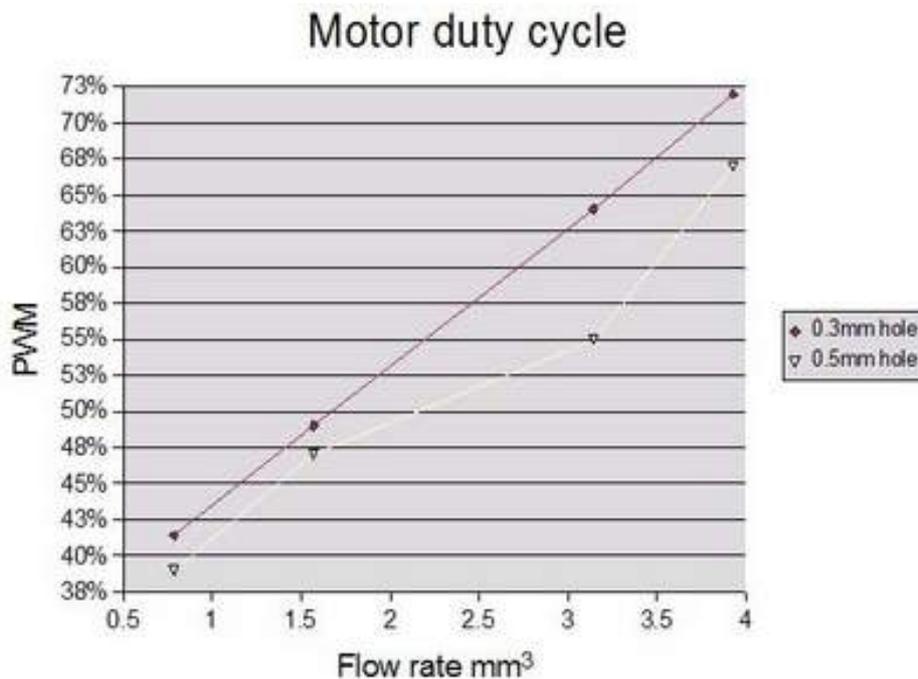
The sleeving I used is already looking sad so I ordered some PTFE sleeving to replace it.

# Extruder spits out its dummy

Sunday, 2nd March 2008 by Nophead

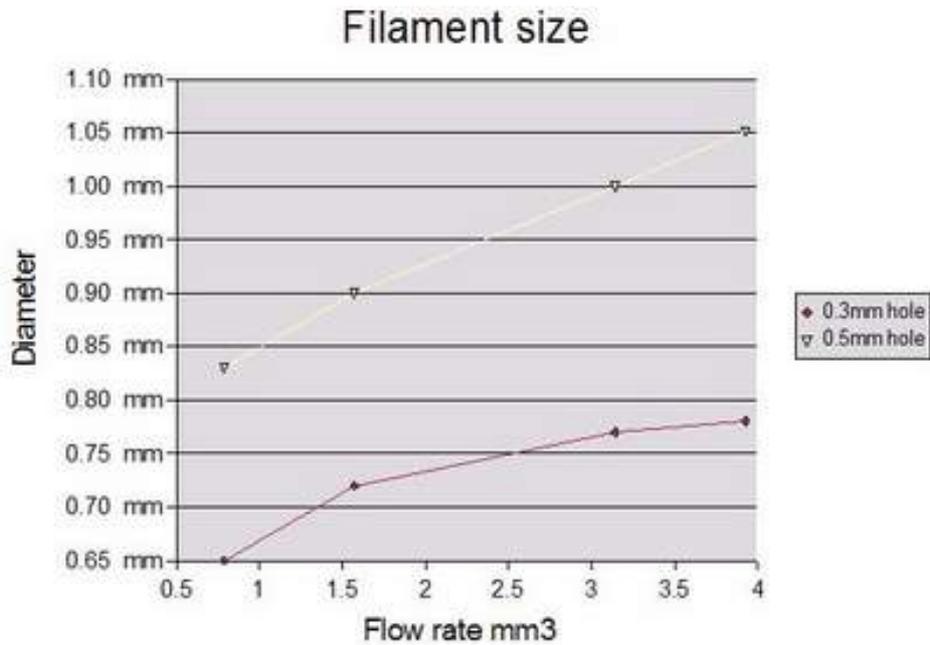
My extruder's heater barrel jumped out of the PTFE insulator so I am back to where I was two months ago with nothing extruded except some test filament and a couple of rafts.

I drilled out the nozzle aperture to 0.5mm to reduce the pressure in the PTFE. I ran the extruder for a while at different flow rates and monitored the motor duty cycle and measured the filament diameter before and after I drilled it. Here is how the motor duty cycle varies with flow rate with different hole sizes:-



Assuming the point on its own is measurement error rather than a weird anomaly, then the torque required is proportional to flow rate plus a constant for mechanical friction, as I had discovered before. Surprisingly, reducing the hole diameter 40% and thus its area by 64% only increases the torque about 5%, which is hard to rationalise.

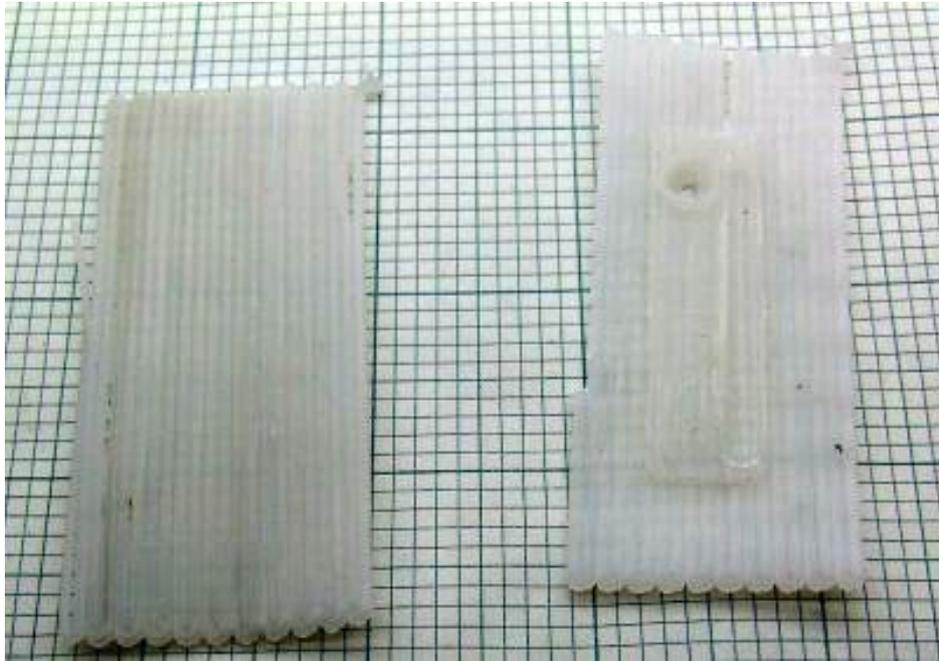
This is how the filament diameter varies with flow rate for the two hole sizes :-



As I found before with a 0.5mm hole, the die swell is pretty much proportional to flow rate plus a constant explained by there needing to be a minimum pressure before the HDPE flows. With the smaller hole the die swell is greater, as expected, but it levels off as the pressure increases. Presumably there is a limit to how much the plastic can compress and expand. I expect that the 0.5mm hole curve would level off as well at higher flow rates. The die swell as a percentage is about the same at the start of the graph for the 0.3mm hole as it is at the end of the 0.5mm hole's curve.

The die swell I get from the 0.5mm hole is less than it was from my previous nozzle. I think that is because the hole is now shorter.

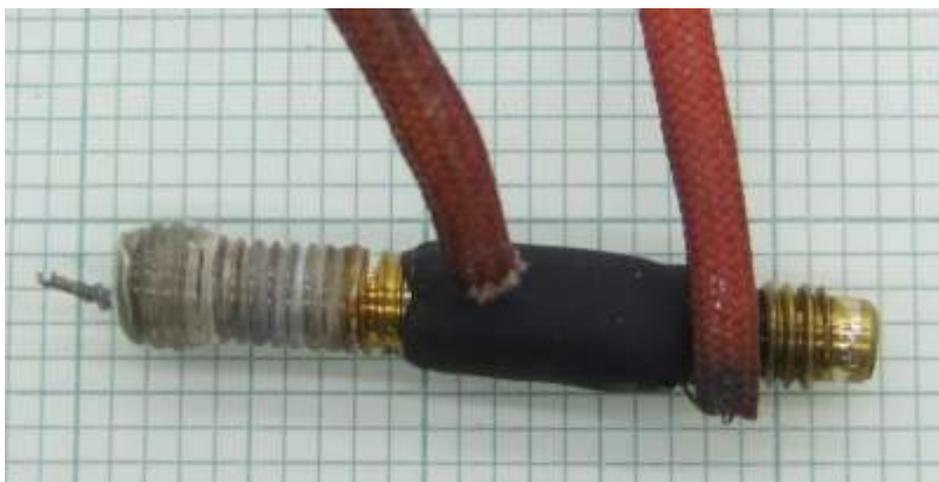
Other things I have noticed with the refurbished extruder is that the overrun is much worse. I.e. after switching off, the filament continues to flow for longer. Perhaps this is the downside of a shorter outlet hole or perhaps for some reason the amount of molten plastic in the extruder is now greater. On the positive side the problem of modulated filament width, that was due to my pump screw bearing lands being eccentric, is now solved. The raft I managed to make (left) is a lot neater than the last raft the old extruder made (right).



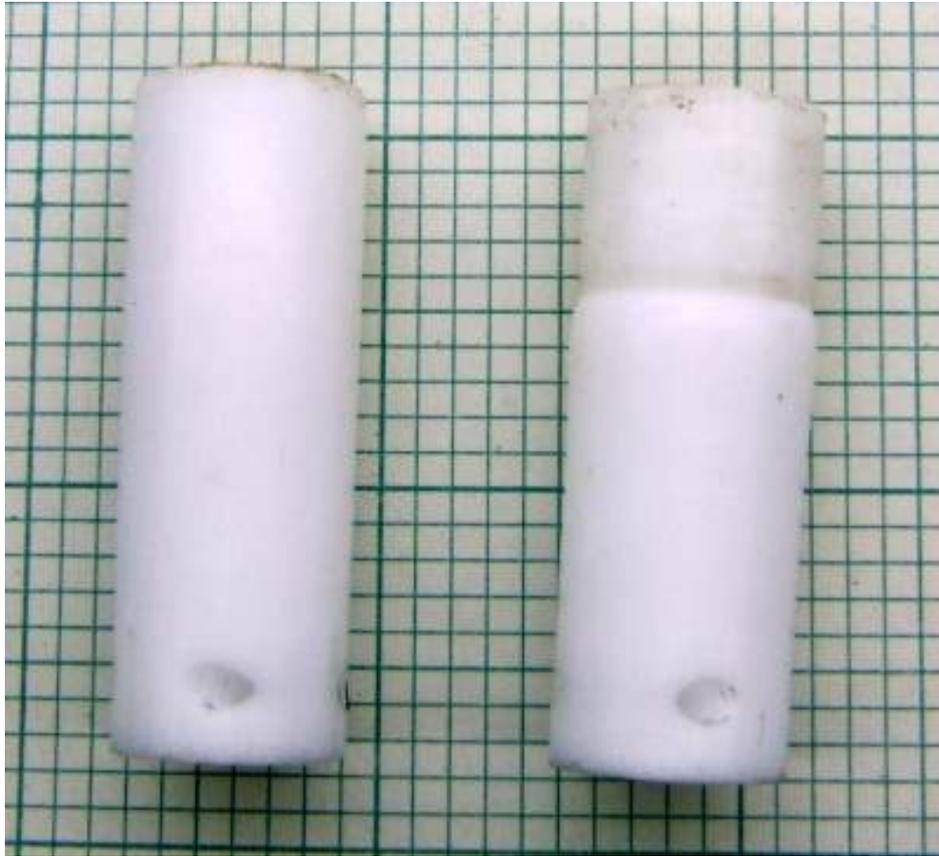
Note that I have boosted the contrast, they are actually both white.

Another thing I learned was that the PTFE is  $\sim 0.5\text{mm}$  longer at  $200^\circ\text{C}$  than it is at room temperature, so I have to calibrate the z-axis while it is hot. I hadn't noticed this before but I checked the thermal expansion coefficient and this figure is in the right ballpark. The brass nozzle expansion is an order of magnitude less.

So that was it for the new extruder as the heater barrel jumped several threads on the PTFE insulator and the nozzle buried itself into the bed, which is now starting to look like the surface of the moon. The reason? Well the thread is not stripped but it is now  $1.3\text{mm}$  too big all the way along. This is despite the fact that the outside of the PTFE tube was constrained by a copper pipe. You can see this from the HDPE left on the heater nozzle :-



The PTFE is in a far worse state after less than one hour use than the previous one which lasted hundreds of hours.



The PTFE is from the same rod and machined in exactly the same way. The pressure in the system, if anything would be less than before because the hole was the same size but not as deep. The only differences are the heater is closer to the PTFE and I had a copper pipe over the end to stop it expanding. Somehow the inside expanded uniformly, while the outside was constrained. The only explanation I can come up with is that it got too hot and melted. I was only running at 220°C when it happened whereas the old nozzle was used at 240°C. It is closer to the heater but as the brass runs inside it I can't see that would have much effect. The copper pipe on the outside may have made it a bit hotter but I am at loss to explain this dramatic failure.

# Cerastil and soap stone

Saturday, 8th March 2008 by Nophead

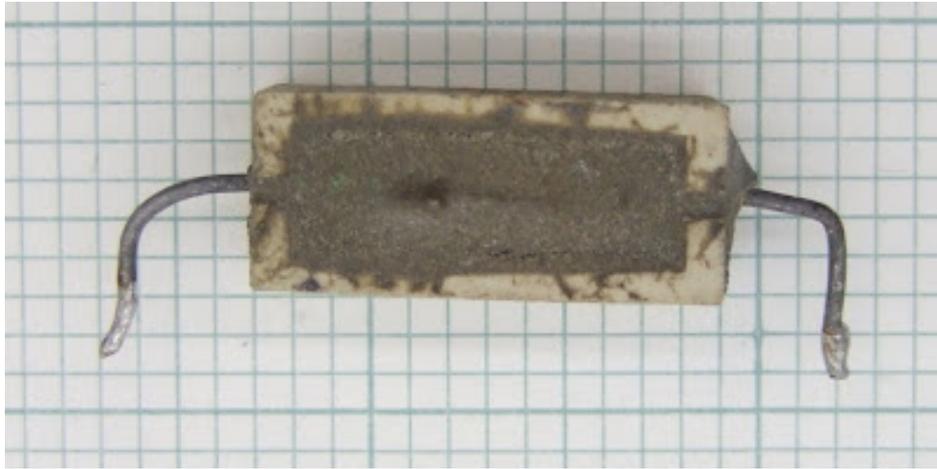
As a bit of light relief from continually repairing my extruder I decided to have a play with the Cerastil H-115 high temperature cement that I have bought.



The minimum quantity that I could buy was 1Kg, which cost aver £100 including shipping and VAT. You only need a couple of grams to make an extruder heater so it is actually cheaper than things like J-B Weld.

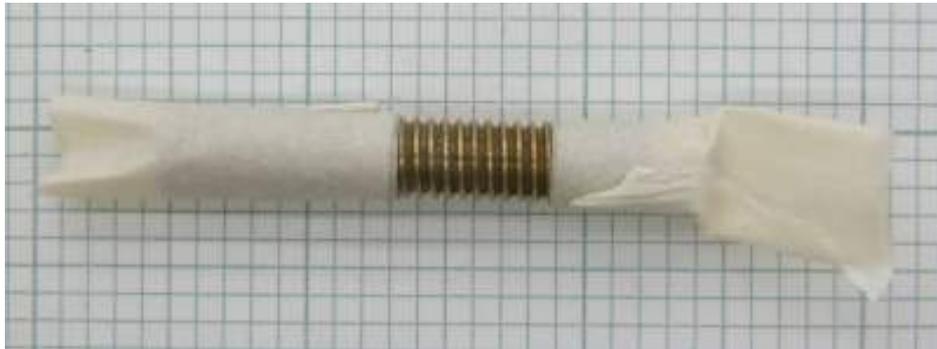
It is labeled as a hazardous substance and comes with a material safety data sheet which says it can't be disposed of in domestic waste and must not enter the sewage system. The hazardous components are identified as potassium silicate and sodium fluorosilicate. When I looked them up on the web I found that the former is added to growing medium and in cosmetics and the latter is one of the chemicals added to water for fluoridation. So they don't seem very hazardous but I suppose it's a matter of concentration.

I am assuming that once it has been cured, by the addition of a little water, that it is then no more hazardous than a ceramic potted resistor like this :-

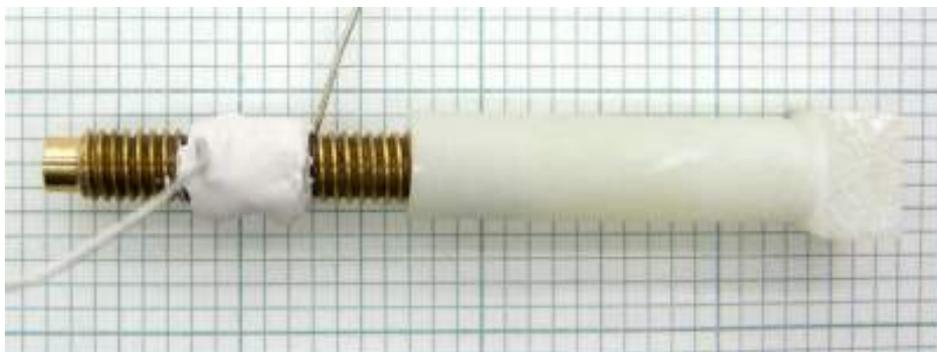


We are no longer allowed to put electronics in domestic waste in the UK but you can just take it to the local tip.

I masked a brass heater barrel and applied a thin layer.

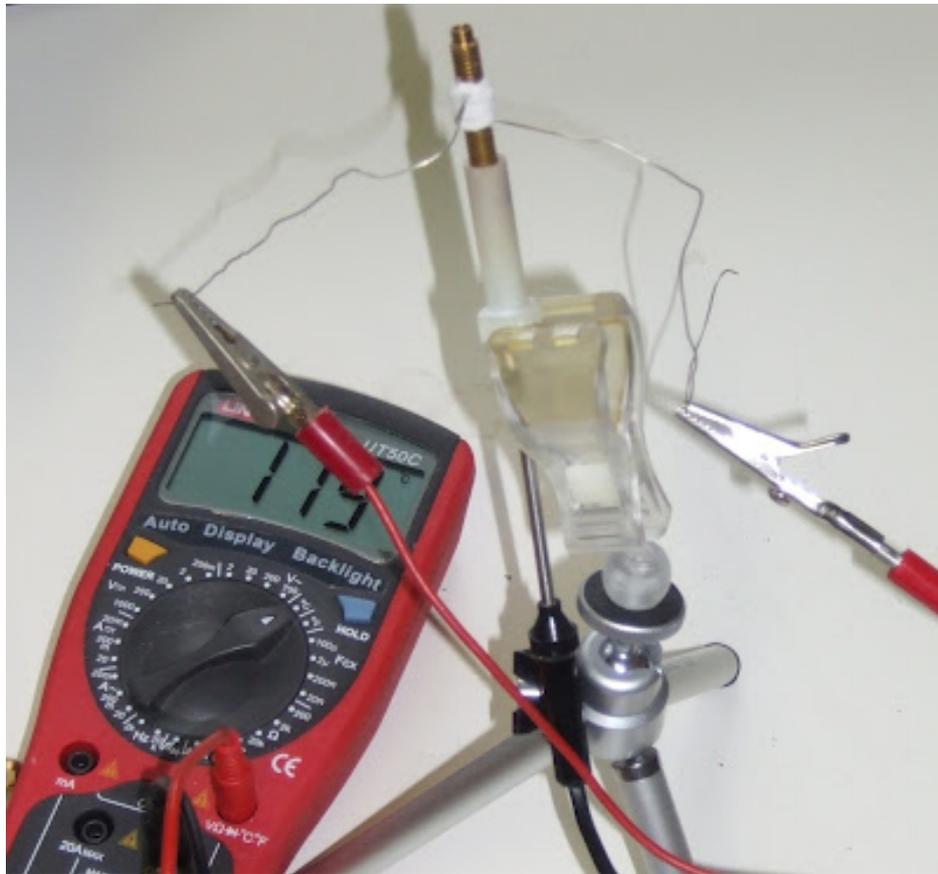


I left it to set for 24 hours and then wound it with two strands of 0.1mm nichrome twisted together. That gives me just 110mm for 8 , to keep the heater short. I attached copper wires with high temperature solder and then put a thicker layer of Cerastil over the top. I then left it another 24 hours to cure.

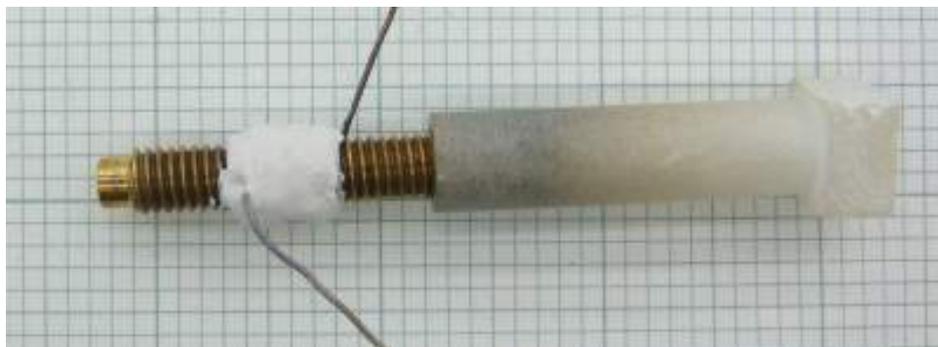


It looks a bit lumpy because of the solder joints underneath.

I mounted it in an insulator that I turned from soapstone and ran it for a few hours at  $\sim 290^{\circ}\text{C}$ .



The bottom of the soapstone barrel got to about 120°C. After the test the Cerastil looked exactly the same, unlike J-B Weld which goes very dark. The soapstone did discolour though at the hot end.



So where has this experiment taken me on my quest to make a durable extruder that covers the full range of thermoplastics? Well I will definitely be using Cerastil from now on as it seems the perfect adhesive for potting heaters, not surprisingly as that is what it is designed for. It is a high temperature adhesive that is a good electrical insulator and a good thermal conductor. I am not sure I can recommend it for the RepRap project though because it is very specialist and not widely available

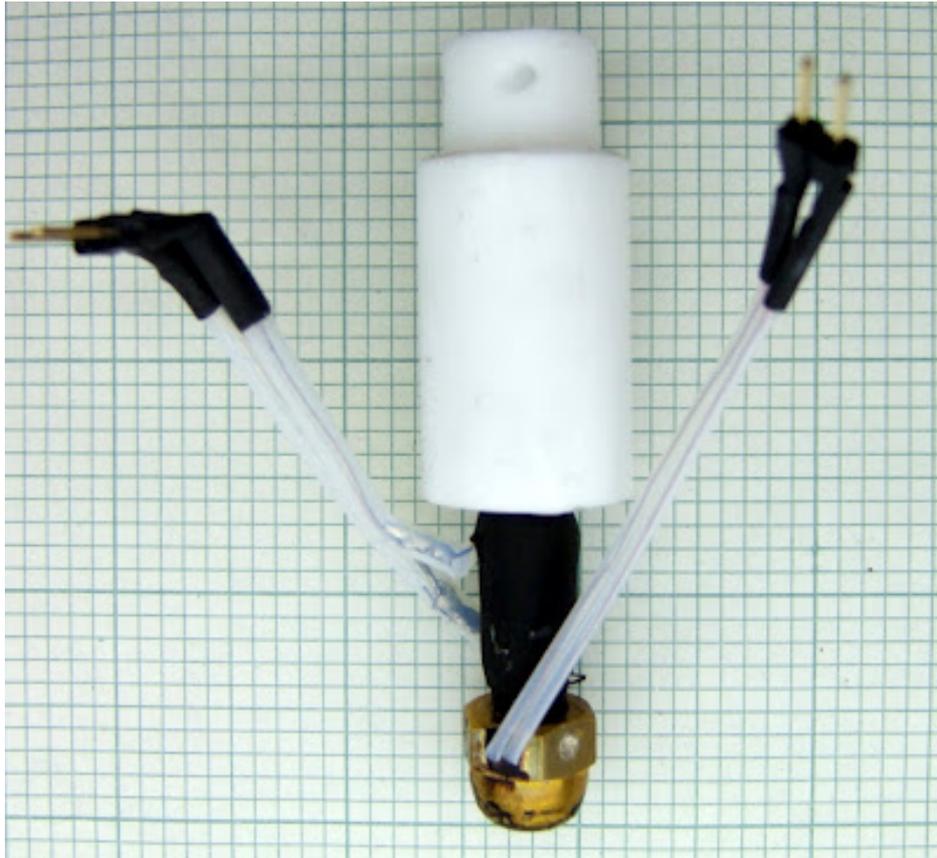
I am also not sure about the soapstone. I was surprised it changed colour but I don't know if it matters or not. It looks like it would need to be twice as long, or have a heatsink at the cool end. I am also a bit worried about its strength.

# Back up and running?

Saturday, 8th March 2008 by Nophead

I rebuilt my extruder again and this time it lasted long enough to complete a test object so hopefully I can finish my research into HDPE FDM before moving on to PCL and ABS.

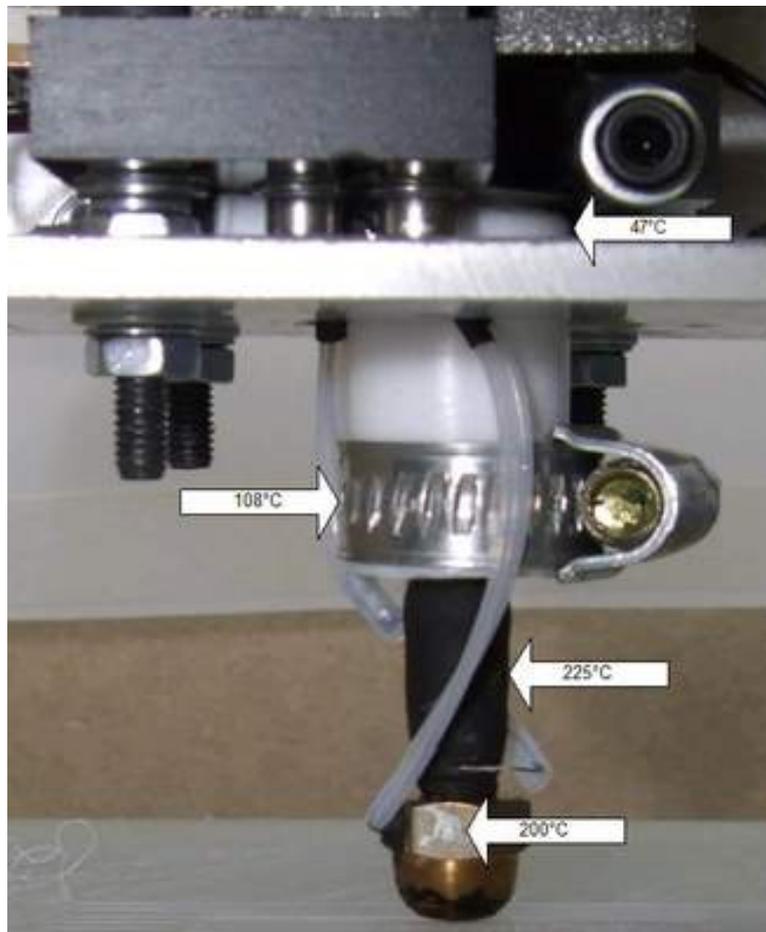
I replaced the 12mm diameter PTFE barrel with the recommended 16mm. Rather than make a new clamp I turned down the top end to 12mm.



I also replaced the woven insulation I was using with PTFE insulation. This is good for 250°C, which is fine for the thermistor but still a bit low for the heater. With this heater I brought out the nichrome tails which probably get hotter than the covered part of the winding. I think I prefer the way I have made my other heaters, which is to put the connections to the copper wires under the heater insulation. That way the copper wires never get any hotter than the body of the heater.

I put a pipe clip round the end of the PTFE to compress it against the screw thread. In an attempt to find out why my previous PTFE barrel deformed so much I made some temperature measurements with a different thermocouple to the one I used before, just in case it was faulty.

These are the temperatures I get with my software set to 200°C :-



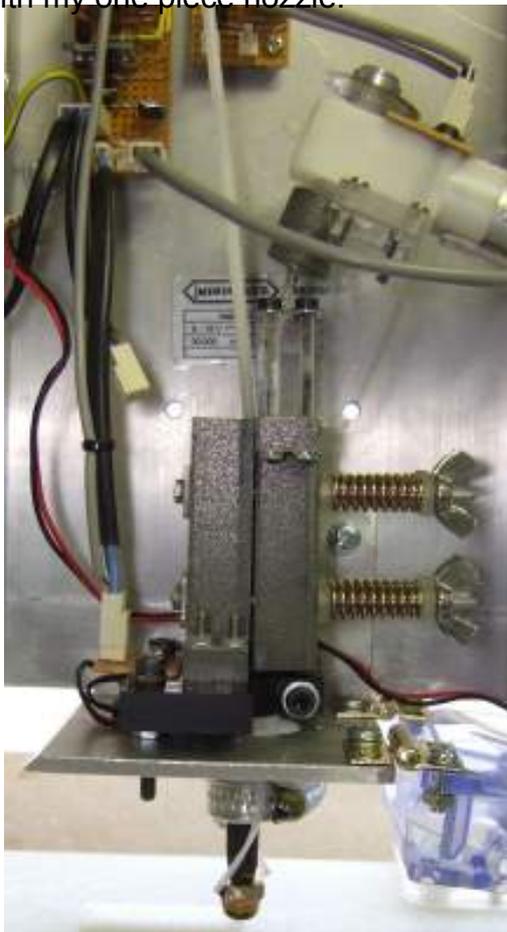
The control of the nozzle temperature is very good, +/- 1°C. The other measurements show just how good an insulator PTFE is compared to the soapstone I mentioned in my previous article.

I think my problems stem from the fact that the heater barrel is quite a bit hotter than the nozzle. With the fan on, cooling the nozzle, the temperature difference will be even higher. It must have reached the point where PTFE starts to melt. I will try extruding without the fan from now on as I think that is what causes the PTFE and J-B Weld to give up. I might need inter layer pauses.

Compared to my first attempt at the extruder I have made the following improvements :-

- The steel cable for the flexible drive is now the recommended 3mm rather than 2.5mm.
- The drive screw has been replaced with one that has correctly centered bearing lands. This completely fixes the modulated filament I was getting before.
- The springs are much stronger which means I don't need to tighten them as far, making assembly quicker.
- The lock nuts on the studding have been replaced with plates which also make assembly and disassembly easier.
- The PTFE barrel is now the recommended 16mm rather than 12mm.
- The PTFE barrel is pinned into the clamp rather than relying on friction alone.
- The heater barrel is held into the PTFE with a pipe clip.
- The nozzle is now removable and has a shallower and tapered exit hole.
- The thermistor is closer to the heater so my on off control cycles much faster and keeps within

+/- 1°C compared to +/-3°C with my one piece nozzle.



So far I am finding that without the fan I need to extrude slower to get the same results I was getting before.

# The pros and cons of nozzles

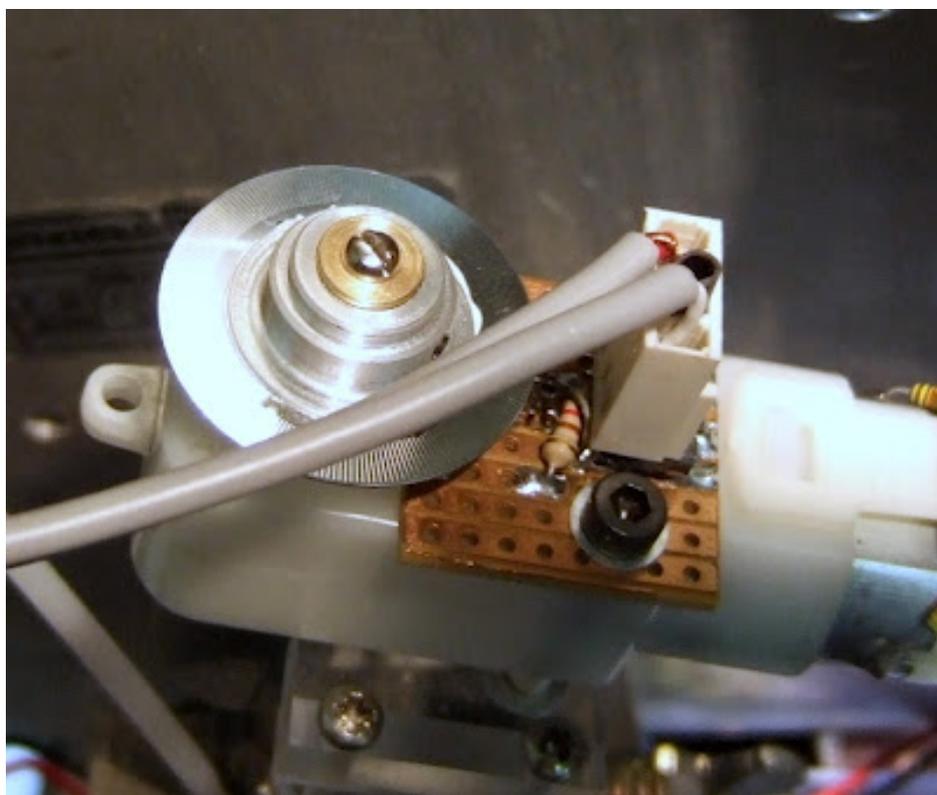
Thursday, 13th March 2008 by Nophead

HydraRaptor seems to be running reliably again, touch wood. I did have one scare when it started making noises like a machine gun when I had left it running unattended. It turned out that the shaft encoder code wheel on the extruder motor had fallen off. That caused the firmware to think it was far behind and so it applied maximum power in an attempt to catch up, which caused the GM3 gearmotor's torque limiting clutch to slip. I added it to the list of sanity checks to put in my extruder firmware :-

- If the shaft position gets more than, say, half a turn behind then give up.
- If the thermistor resistance is too high then the thermistor is open circuit so turn the heater off.
- If the thermistor resistance is too low then the thermistor is short circuit.
- If the heater has been on for more than 5 seconds and the temperature has not risen then the heater is open circuit.
- If the heater has been off for 5 seconds and the temperature has not dropped then panic, the transistor is short circuit.

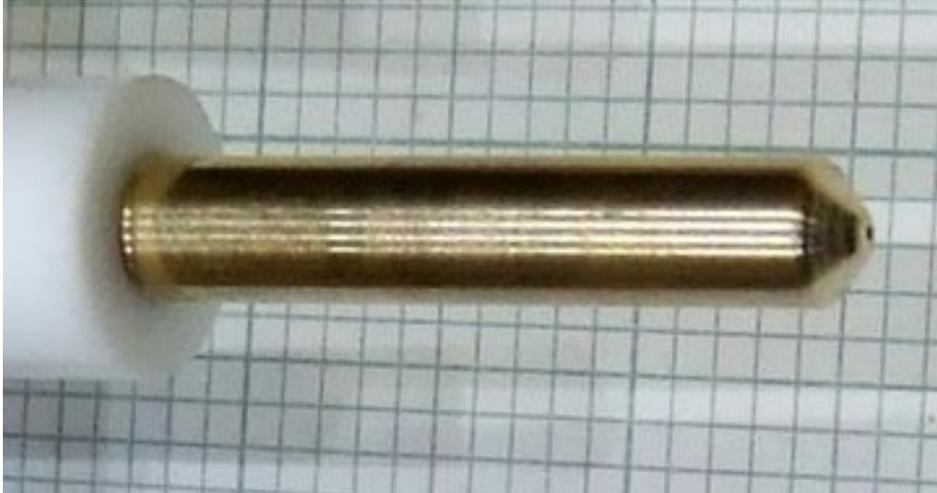
All these checks are necessary for safe unattended operation in my opinion.

The solution to the code wheel problem was to extend the shaft of the GM3 with a piece of brass rod :-

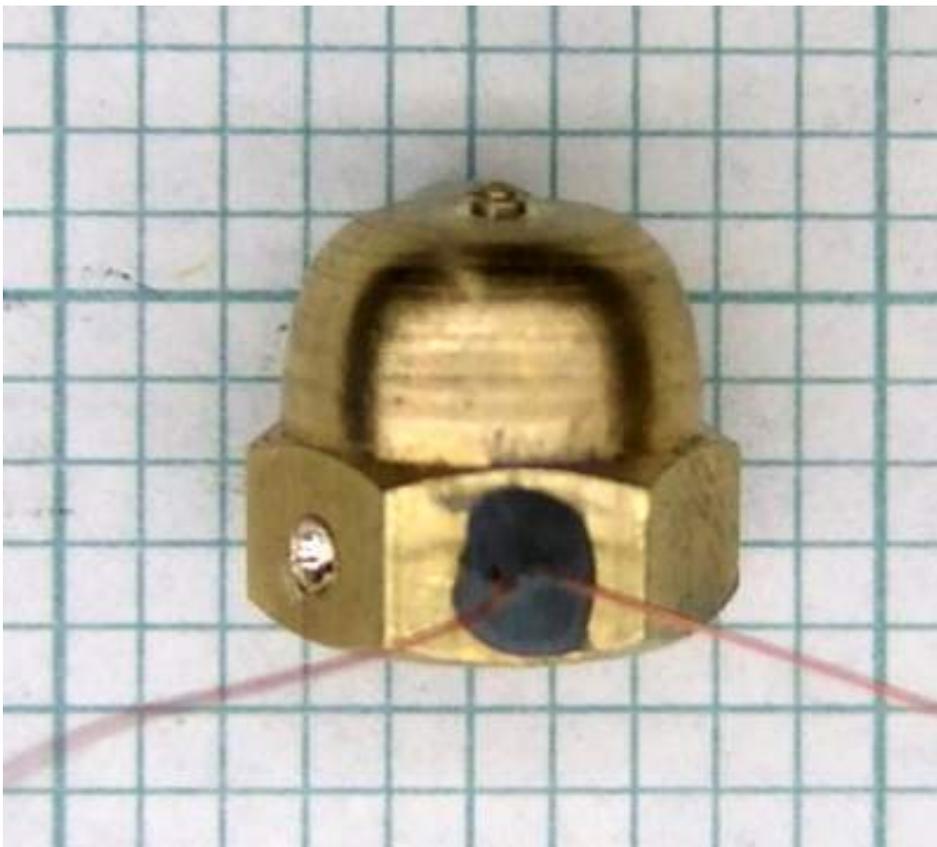


I have managed to perform quite a lot of tests with HDPE and it is clear that the new acorn nut nozzle behaves quite differently to the previous one piece design.

The original nozzle looked like this and had a 0.5mm hole that was about 0.6mm deep: -



The new nozzle is made from an acorn nut turned to a point. It also has a 0.5mm hole, but it is tapered at about 45° so the part of the hole that is 0.5mm diameter is very thin :-



The differences this seems to make are: -

1. The die swell, i.e. the amount the filament expands from the hole diameter, is a little less.
2. The amount of filament that extrudes after the motor is switched off has increased quite a lot. The excess is wiped from the nozzle, but by the time the head has moved from the brush back

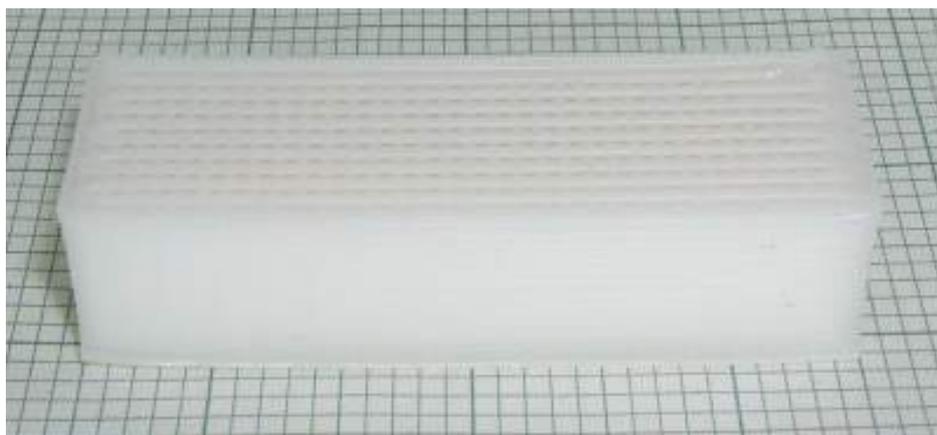
to the workpiece, a few more mm have leaked out making for a messy line start. I think this is because the shorter exit hole makes it easier for the plastic to escape.

3. If I move the head quickly with the extruder off, then the filament snaps. It quite often leaves a blob that sticks to the workpiece. With the longer hole it stretched to a long thin string rather than snapping.
4. I used to be able to lay down 0.5mm filament at 16mm/s by stretching, but now I can only do this reliably at 8mm/s as the filament has a tendency to snap. I think it is too easy to pull it from the new shaped hole.

When stretching the filament it has a greater tendency to cut corners. I think this is mainly due to not running the fan, but may also be because the nozzle is too pointy. A wider nose will help to push the corners down.

I can't run the fan because the heat loss from the bigger nozzle causes the heater to work harder, raising the temperature of the barrel above the point where the PTFE distorts. I need to insulate the nozzle so I will try making a new one similar to this one with a PTFE cover over it.

Here is about where I am at with extrusion quality: -

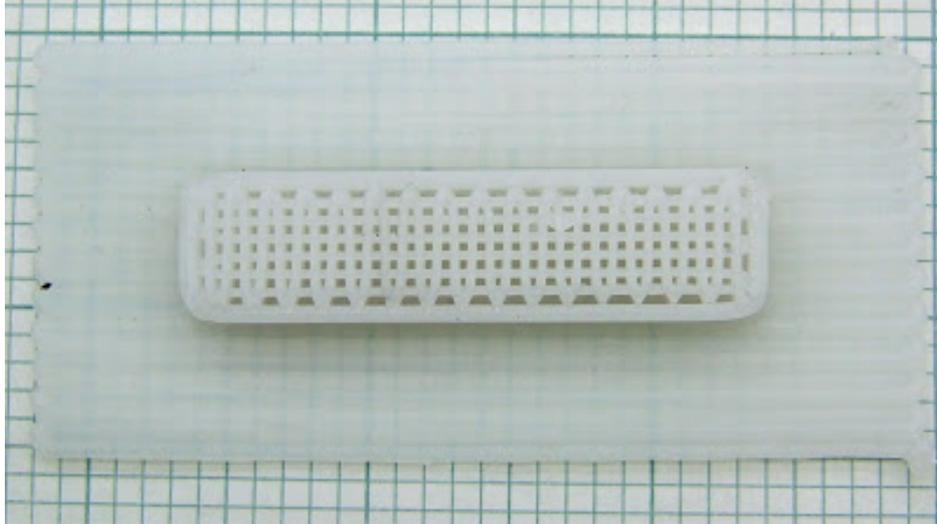


This is a rectangular block about the size of the extruder pump (60 x 20 x 15mm), with a 50% fill. I forgot to put a top surface on it but that is perfectly possible. It was extruded at 220°C (measured at the nozzle) with filament stretched to 0.75mm at 7mm/s. The layer height is 0.6mm and the pitch is 0.9mm. Some warping still evident but it has come a long way from my first attempts.

# Filling in

Sunday, 16th March 2008 by Nophead

I have been experimenting with various infill patterns. Here is a 40 x 10mm block made with 0.5mm filament at 50% fill: -

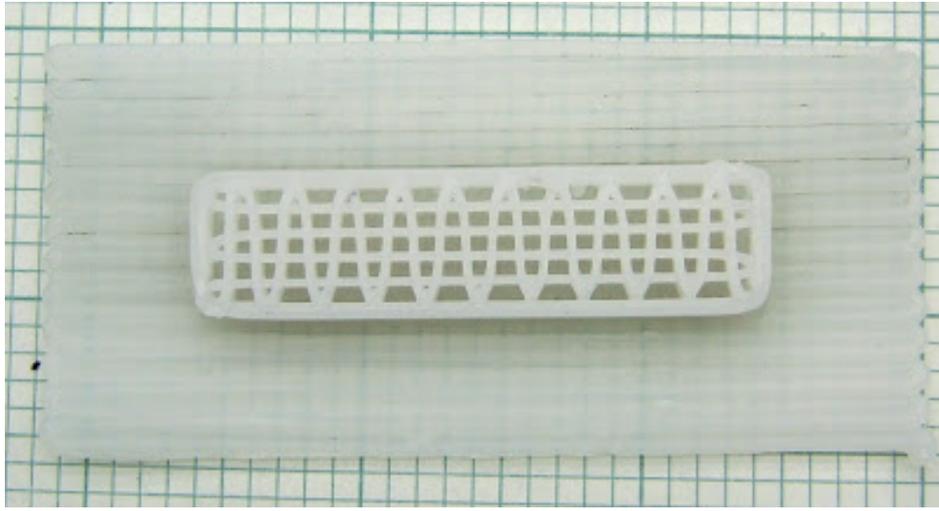


For simplicity I used alternating horizontal and vertical lines rather than diagonal. The layer height is 0.4mm so the width is about 0.6mm and so are the gaps. A couple of things that weren't obvious to me at the beginning were: -

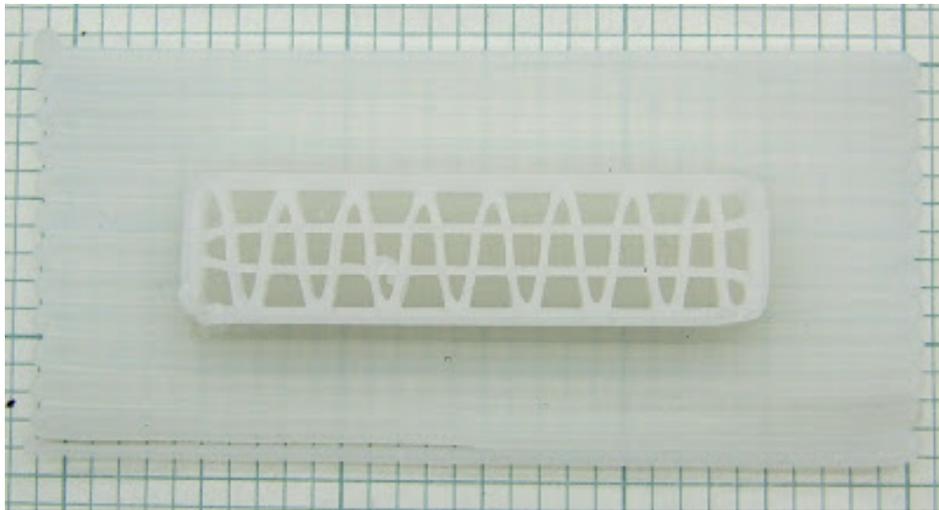
The first and last lines of the fill must be adjacent to the outline so that the U turns on the alternate layer above have something to rest on, otherwise they curl upwards or downwards and don't bond to the outer skin. That means adjusting the gaps slightly to make the overall width correct. When the fill is 100% I adjust the filament width slightly to exactly fill the interior. Easy enough with a rectangular object but probably not with an irregular polygon.

The fill lines probably should line up with the those two layers below so that the intersections form a solid column of filament from top to bottom, otherwise some sag may be expected. Again trivial for rectangles but could get tricky to generalise.

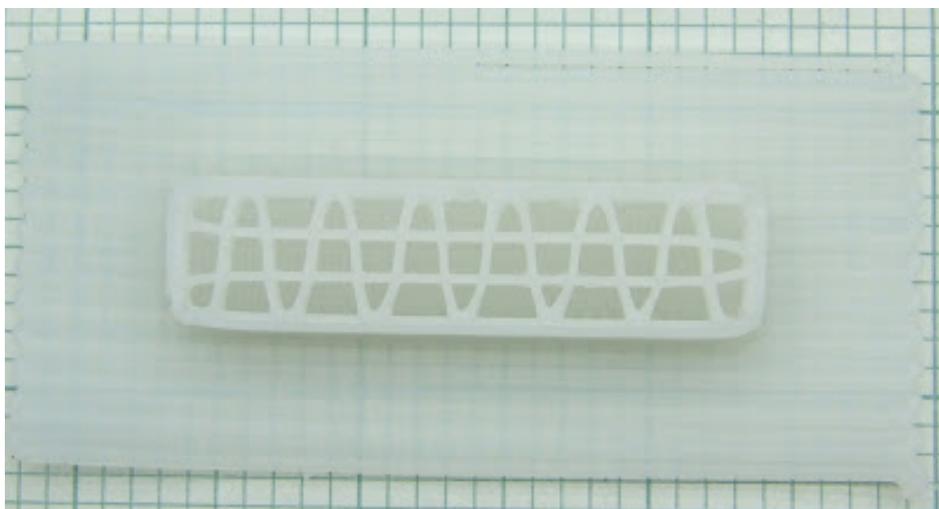
Here is 33% fill, i.e. the gaps are about twice the filament width: -



This is 25%. Notice how, although the filament is laid down in a perfect square wave, when it shrinks it pulls itself to the first harmonic. A physical low pass filter!

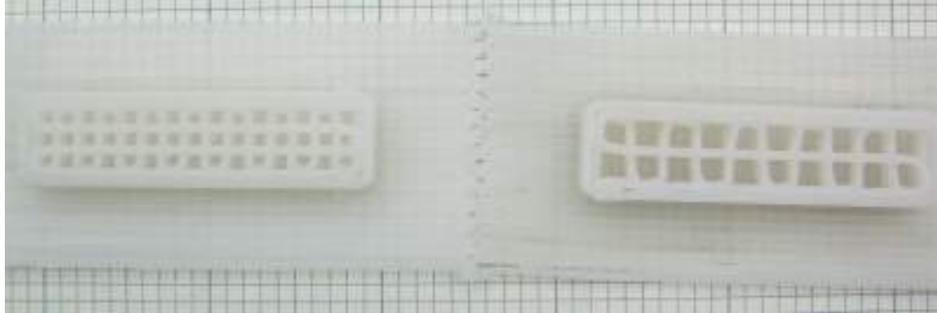


And here is 20%: -



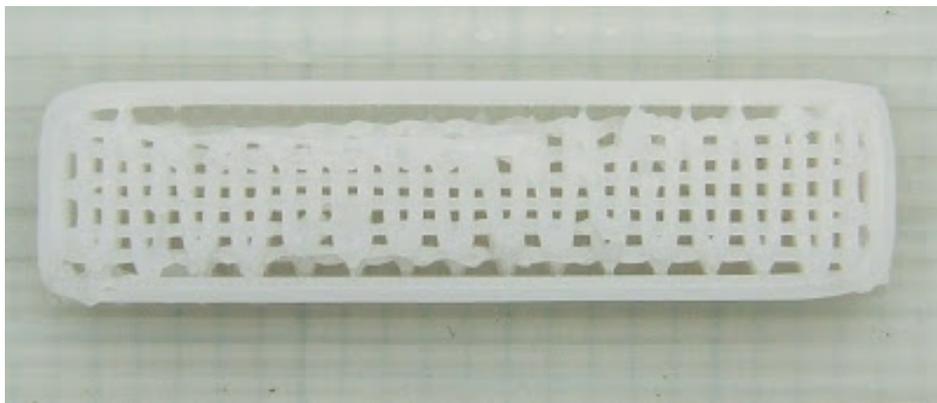
I found that when putting a lid over the top it struggled with an infill this sparse, so I settled on 25% as the limit for making closed boxes.

All the above are done with filament stretched to 0.5mm. When extruding through a 0.5mm orifice, left to its own devices the filament would be about 1mm due to die swell. I decided to try the same pattern with 1mm filament, i.e. with no stretching: -



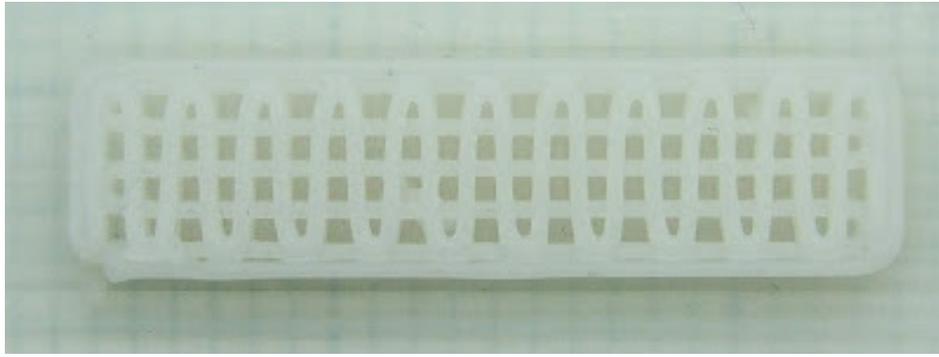
As you can see the filament holds the square wave better but what is not obvious is that without stretching it sags a bit in the gaps where it is not supported from below. So some stretching is beneficial, when it comes to spanning voids, but it does increase corner cutting.

As I mentioned before, with my old nozzle, I could extrude 0.5mm filament at 16mm/s. This is what happens with the new one which has an exit hole which is too shallow: -



One unfortunate characteristic of FDM is that errors tend to be cumulative. What I mean by that is if, for example, the U turn of the zig zag fails to bond to the outer wall then that causes the next layer to have nothing to rest on, so that fails as well. The defect then propagates all the way up the object. With 100% fill, any errors tend to have less effect on the layers above.

Rather than slow down my experiments I decided to go to 0.75mm filament at 7mm/s until I make a new nozzle. Here is a 50% fill: -



I also added a bit of overlap between the fill and the outline at the u-turns to get a better bond.

So does the infill density affect warping? I made several test blocks and it looks like the answer is not much. However, I have come to realise that the warping takes hours to fully develop after the object is removed from the base so I will leave them overnight before attempting to make measurements.

# A high temperature extruder?

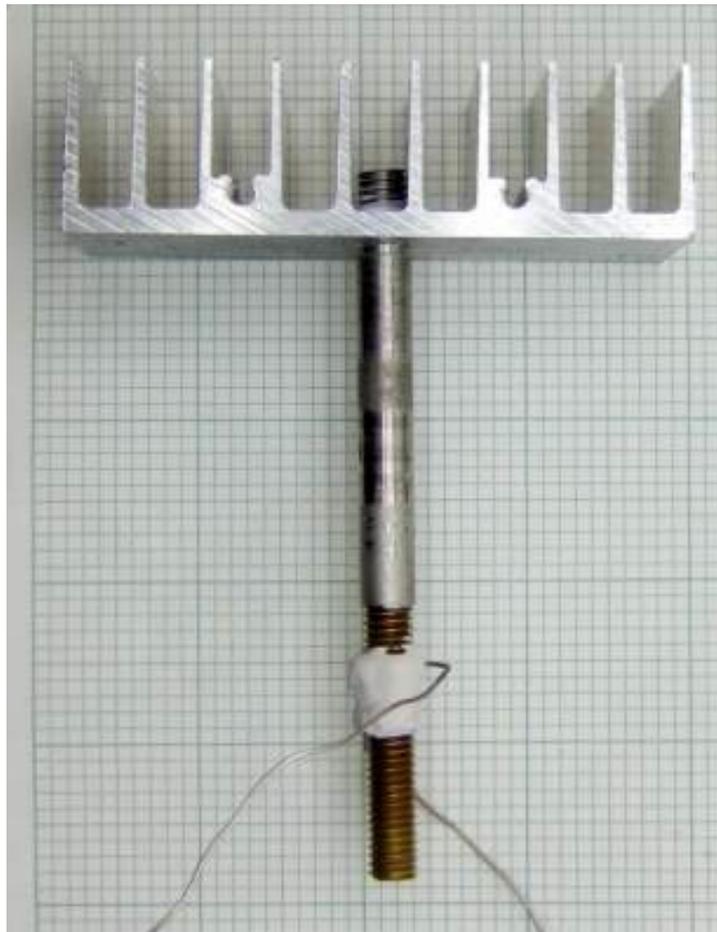
Sunday, 16th March 2008 by Nophead

The standard RepRap extruder can't quite handle the temperatures for HDPE for very long. I have found a high temperature replacement for J-B Weld. The main weak point remaining is the PTFE thermal barrier. PTFE is an excellent thermal insulator but it is not very strong mechanically. It also expands by about 0.5mm at 225°C. Worse than that it seems to slowly creep the more I use it, which makes a mockery of my z axis calibration. Since I got it working again I have re-calibrated it four times and each time it has grown: 0.3mm, 0.2mm, 0.15mm and 0.3mm. I.e. it is now 0.95mm longer than when I built it and a further 0.5mm when it is hot.

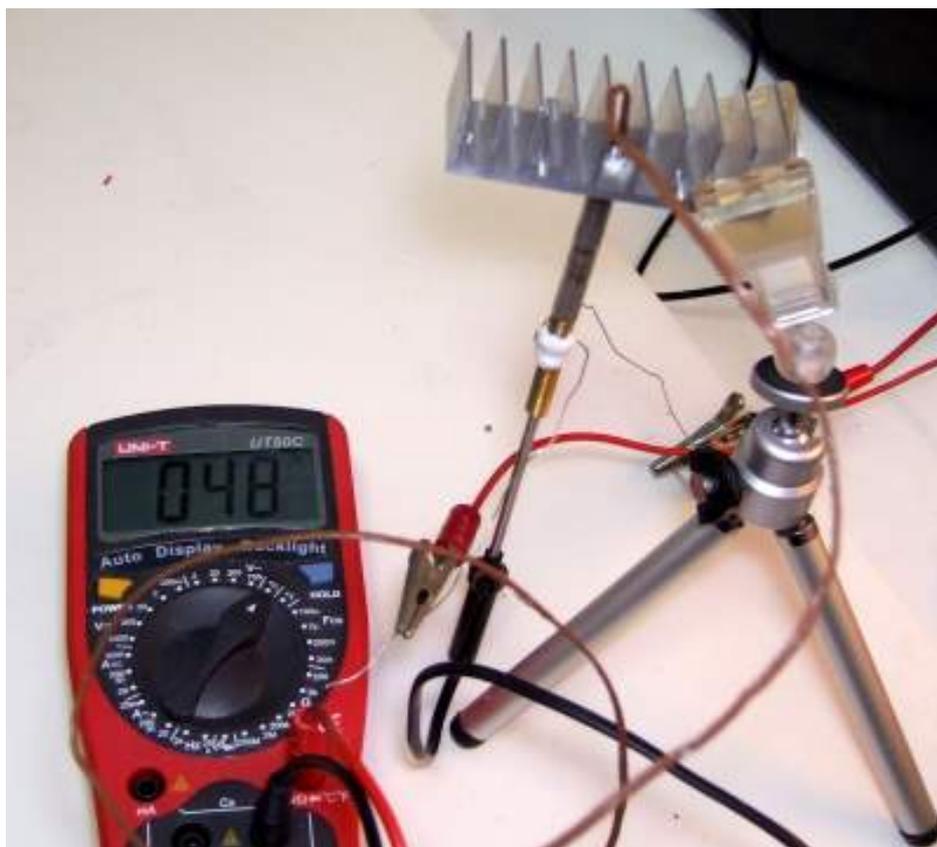
I have come to realise that stainless steel is quite a poor conductor of heat compared to other metals:-

Stainless Steel      Brass                      Aluminium              Copper

I bought some stainless steel pipes on eBay that have an outside diameter of 6.4mm and an inside diameter of about 3.5mm. I cut a 50mm length, tapped it and screwed in into a medium sized heatsink. I tapped the other end and screwed in my experimental high temperature heater. I applied heatsink compound to both threads.



I put a thermocouple in the heater and adjusted the power to get 240°C inside the brass part of the barrel. That only required 7.3W. I put another thermocouple at the top of the stainless steel barrel and that only reached 50°C.



Although this is just a lash up, it looks really promising. I can get the temperature even lower by using a CPU heatsink or a small fan. I will make a nozzle out of aluminium or copper with a built in heater and thermistor.

Not only will this stand temperatures up to the limit of the thermistor, which is 300C, but it is also much more rigid and does not change in length significantly with temperature. It should also reduce the amount of molten plastic because of the thermal gradient down the SS barrel. That should give less extruder overrun.

# Hot maths

Tuesday, 18th March 2008 by Nophead

As the power lost through the stainless steel barrel in my previous post seemed very low I decided to calculate it as a sanity check. I ignored the heat lost from the barrel by convection and radiation. They may be significant now but when I insulate it they shouldn't be.

The outside diameter of the tube is 6.35mm and the bore is 3.6mm, so that gives a cross sectional area of  $2.15 \times 10^{-5} \text{m}^2$ . Its length is 0.05m. The temperature difference over that length is  $240^\circ\text{C} - 50^\circ\text{C} = 190^\circ\text{C}$ . The conductivity of stainless steel is 17 W/mK. So the heat flow is  $17 \times 190 \times 2.15 \times 10^{-5} / 0.05 = 1.39\text{W}$ . That means it isn't very much compared to the total power required, so that matches my observation.

The amount of heat flowing into the heat sink is therefore 1.39W and it raises its temperature by  $30^\circ\text{C}$ , so the heat sink would have to be  $22^\circ\text{C/W}$ . It was just a scrap one I had laying about so I don't have a spec but it is only 70 x 25 x 20mm so that seems in the right ball park.

Sanity checked!

# Infill and warping

Thursday, 20th March 2008 by Nophead

Now that I can create blocks with different infill densities I decided to experiment to see what effect it has on HDPE warping.

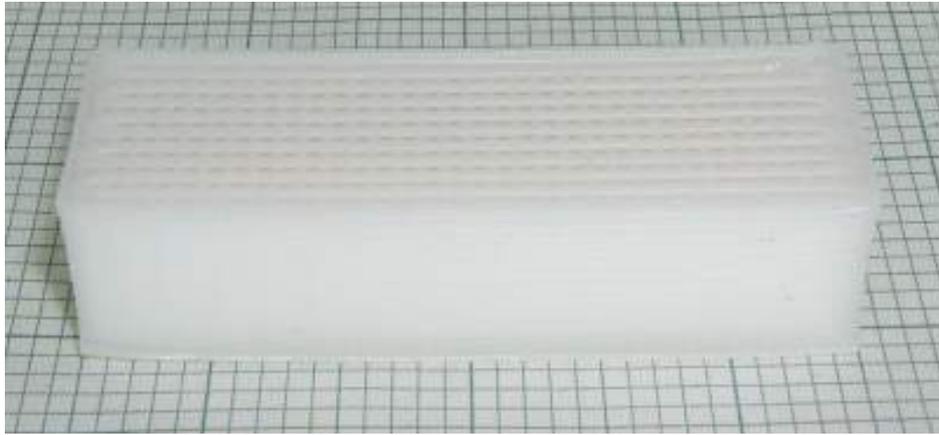
I have been using a standard test shape and a jig made of three nails to make comparative measurements.



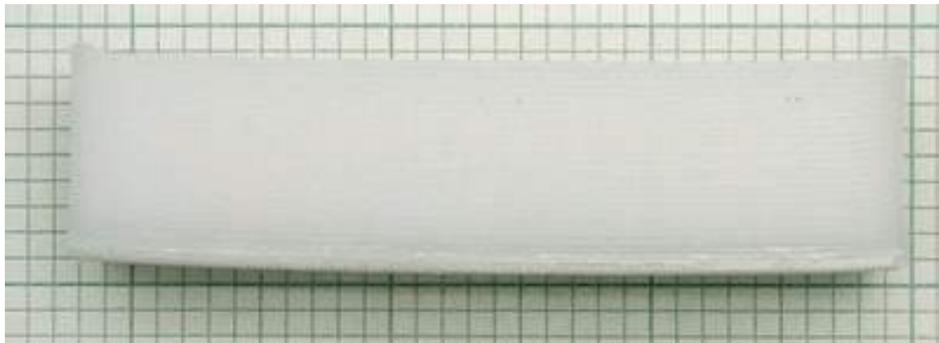
I measure from the middle nail to the base with a pair of digital calipers and subtract the distance to a rule placed across the nails. The figure I get is an average of the amount each end warps upwards. Not very precise because the base is warped the other way as well.

The block is 40 x 10 x 20mm because you need about 40mm length before the warping becomes big enough to measure and 20mm height is about where things start to straighten out. Bigger shapes warp more but obviously take a lot longer to make. Each one of these takes about an hour including making the raft, extruding the block, separating it from the base and measuring it.

The block is held flat while it is stuck to the bed of the machine by the raft. It warps when I remove it. I have only recently noticed that it warps even more when left overnight, so some of my previous tests are not that accurate. For example I was quite pleased when I first produced this extruder sized block :-

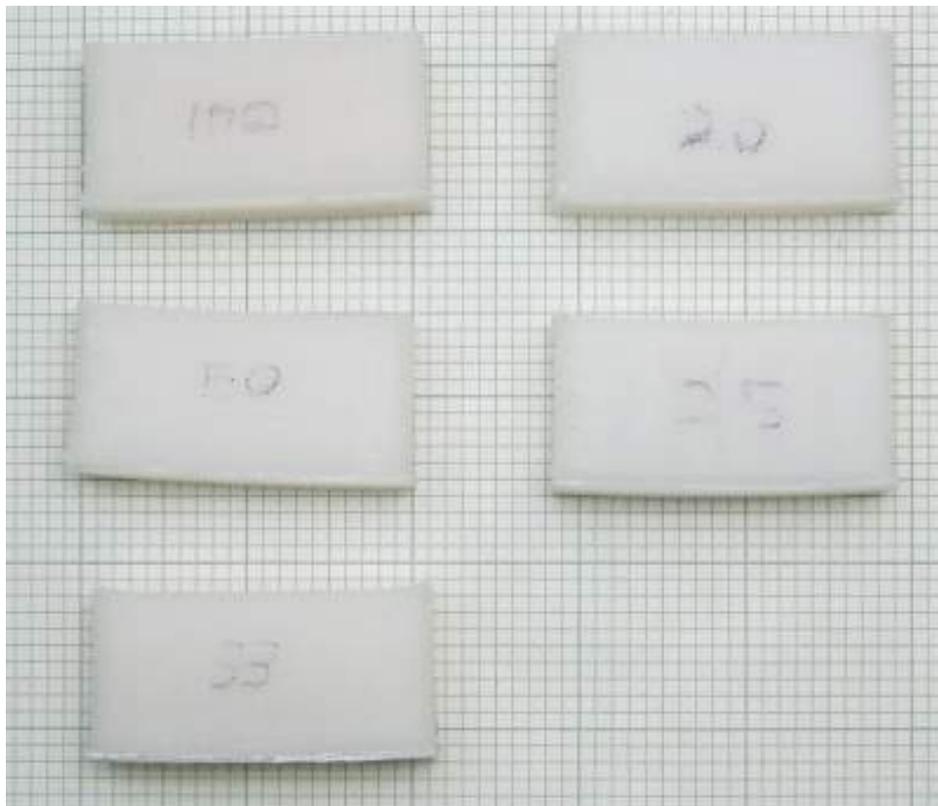


But here it is again photographed some days later :-



Not easy to compare because of the angle but the uplift at each end probably increased from about 0.5mm to 1mm. It implies to me that HDPE creeps when under prolonged strain, not a very good engineering property. That is the main reason PTFE fails in the extruder.

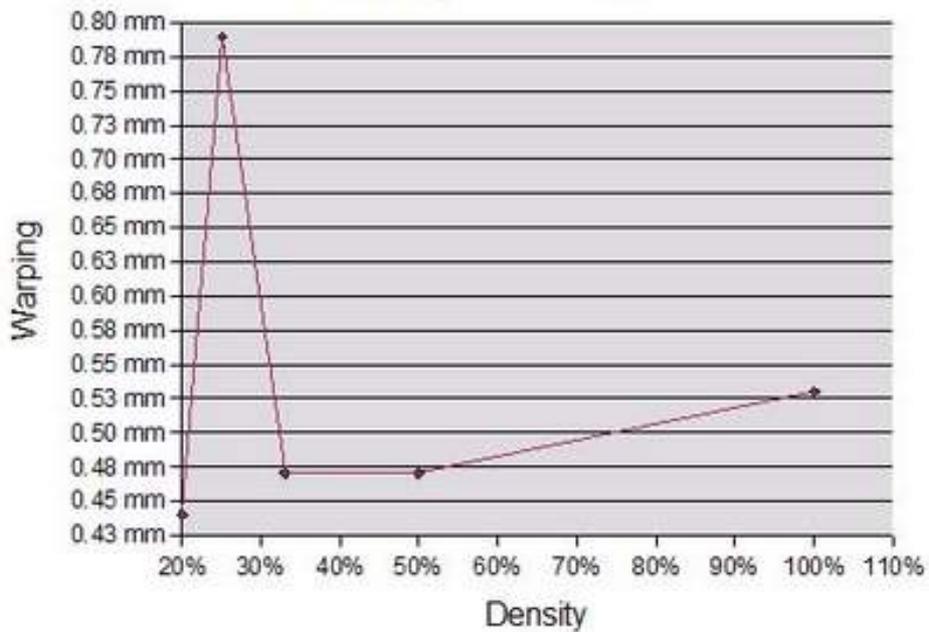
I made the test blocks with different infill densities and left them overnight before measuring them :-



Here are the results: -

Density	Warp
20%	0.44 mm
25%	0.79 mm
33%	0.47 mm
50%	0.47 mm
100%	0.53 mm

## Warping v density

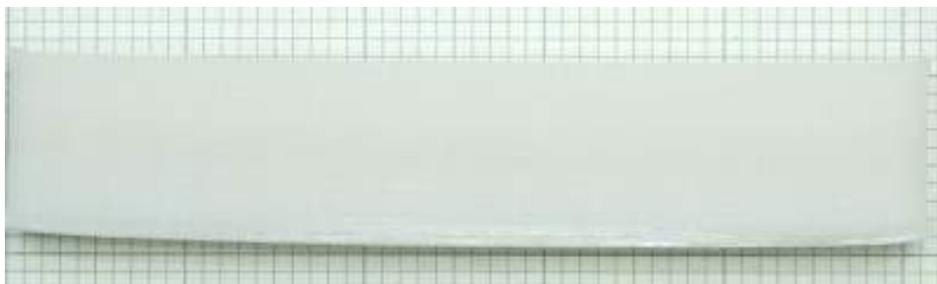


The 33% value looks totally anomalous but that is because I tried a thicker base. Its base is 3mm of 100% fill including the raft, whereas all the other tests begin the sparse fill on the first layer above the raft.

I also tried 1mm filament 50% fill which gave 0.42mm warp showing that not stretching the filament does not give any improvement.

Conclusions: well sparser fill reduces the warping slightly. A thicker base, rather than resisting warping, actually contributes to it. I must point out that once you get less than 50% fill the object is considerably weaker than a solid block.

Finally here is a longer example, which illustrates how warping gets worse the larger the object is. This is 100 x 10 x 20mm with 20% fill. The first time I made it it lifted the raft away from the base. I got round that by increasing the raft temperature by 10°C to get a stronger weld. It was then quite hard work removing it and it caused some damage to the PP bed.



The 40mm section in the middle is only warped by 0.19mm but the ends are well over 1mm. That shows that you cannot compensate for the warping with a crowned bed because it is not a constant curvature. One could probably scan the shape of the base and lay down support material with the inverse curve. I expect it would then pull itself flat.

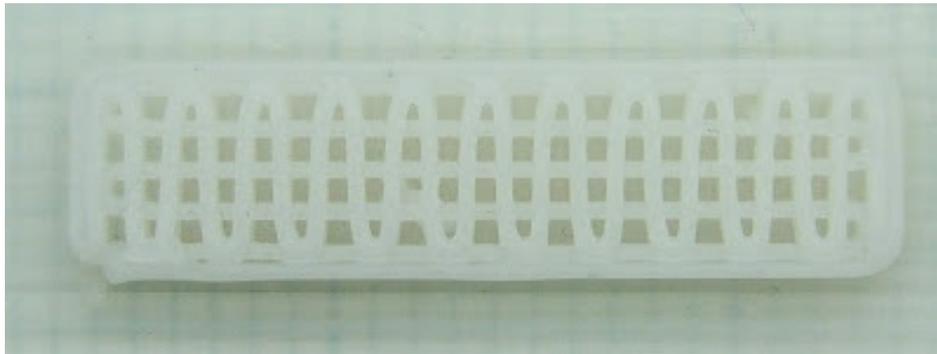
In my next experiment I will try filling the sparse blocks with polyurethane two part thermoset plastic.

# HDPE + PU

Friday, 21st March 2008 by Nophead

Because my test objects are less warped while they are still attached to the polypropylene bed, I had the idea of filling them with something that sets hard to freeze them in that shape. That would also allow me to use a sparse fill pattern, which speeds up the FDM build time, but still get a strong object.

I needed something that was not too viscous so that it would flow in between the mesh of the fill pattern and would set hard.



Polyurethane was recommended to me because it has the consistency of milk before it sets and is strong enough to cast parts for Darwin. I bought some Smooth-Cast 300 which has a pot life of 3 minutes after it has been mixed, and cures in 15 minutes. I choose a fairly fast setting one because it gets hot while curing and I hoped it would soften the HDPE to relieve the stress. It only seems to get to about 50°C though so I don't think that it has much effect in that way.

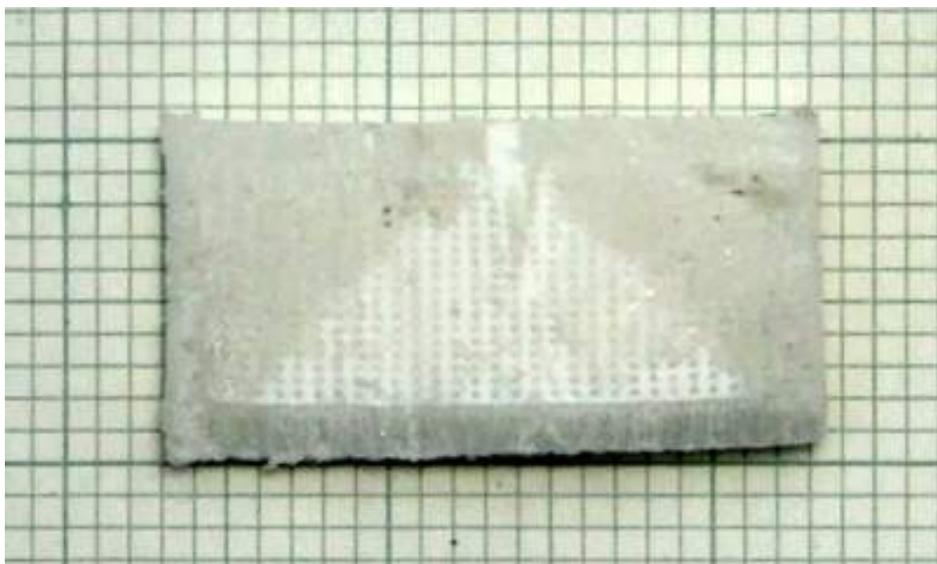
This is the equipment I used :-



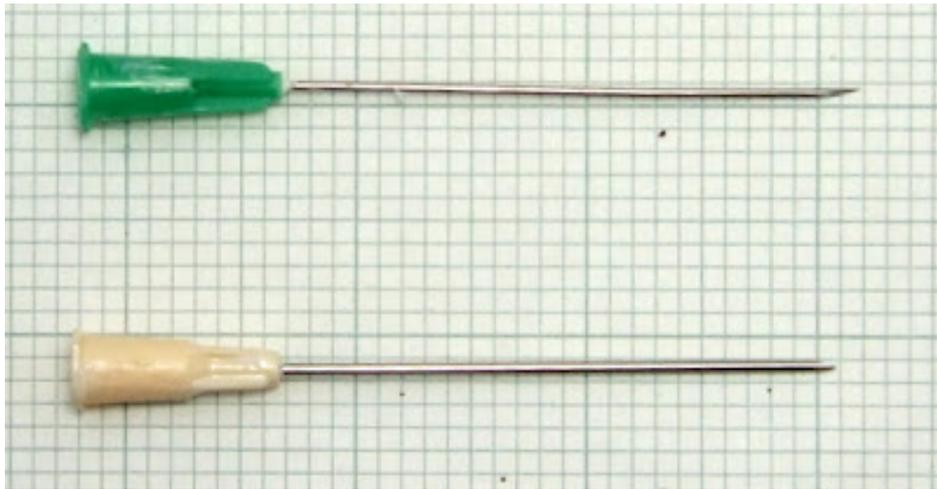
I know the internal volume of my objects pretty accurately so I measure out the required amount of plastic using separate labeled syringes for the two components. I mix it in a small pot before filling a third syringe to inject it. The syringes and pot are made out of polypropylene, which polyurethane does not stick to, so they can all be reused. I haven't found a way of unblocking the needles though.

I made a 50% filled object and drilled a hole the diameter of the needle in the middle that allowed the needle to go to the bottom. I also drilled a small riser hole at each end to let air out. Obviously, with cleverer software these holes could be made during the FDM phase.

The first attempt was a complete failure because the needle blocked when the object was only about 50% filled. Here is a cross section :-



For my second attempt I used a thicker needle, 1mm OD rather than 0.8mm :-



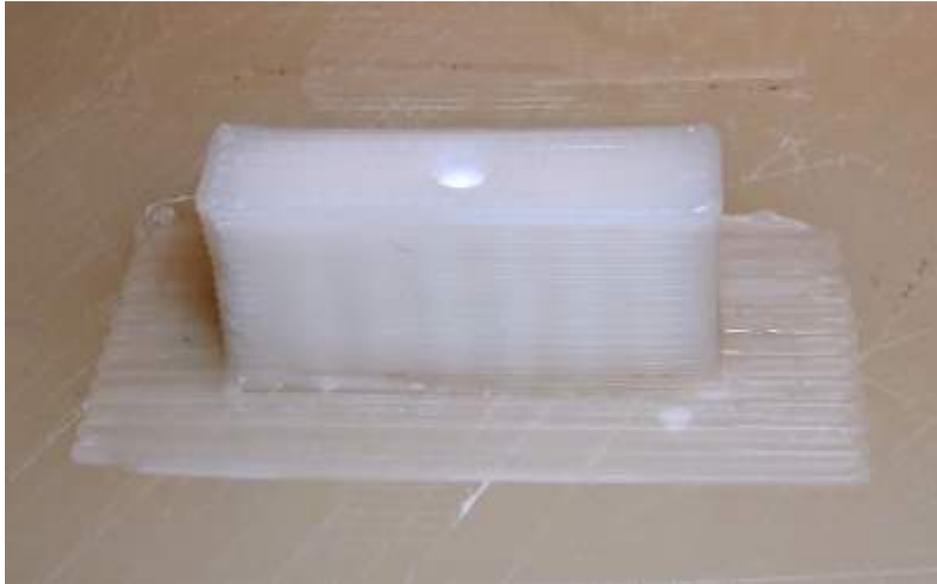
The object filled OK, but just as it became full the plastic in the needle set suddenly but I carried on pushing. The needle popped off the end of the syringe and PU sprayed all over the place. It was a good job I was wearing goggles and gloves but I should also have been wearing long sleeves, a mask and a hat! Fortunately PU does not stick to much, only untreated wood, skin and hair! Where it gets on your skin it burns slightly. Because it is transparent before it sets it is very hard to see where it has gone but when it sets it turns opaque white so it becomes obvious.



It actually sprayed around one quarter of the room. I even got some on my lips which I didn't notice until I tried eating.

What seems to happen is that if you subject the liquid plastic to pressure it accelerates the curing,

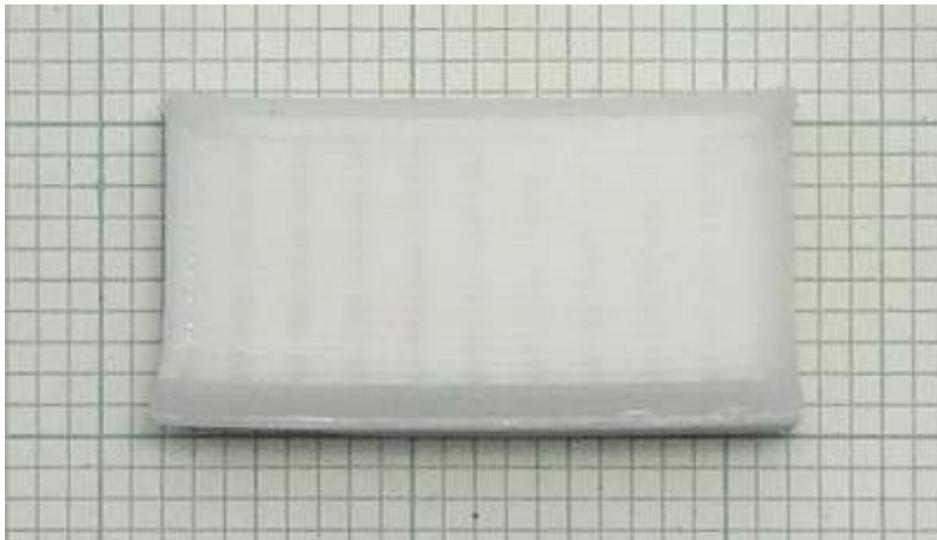
which increases the temperature and pressure creating a positive feedback effect which makes it set suddenly in the needle. I only had two needles and they were now blocked so I did the remainder of my experiments using just the nozzle of the syringe into a bigger hole in the object.



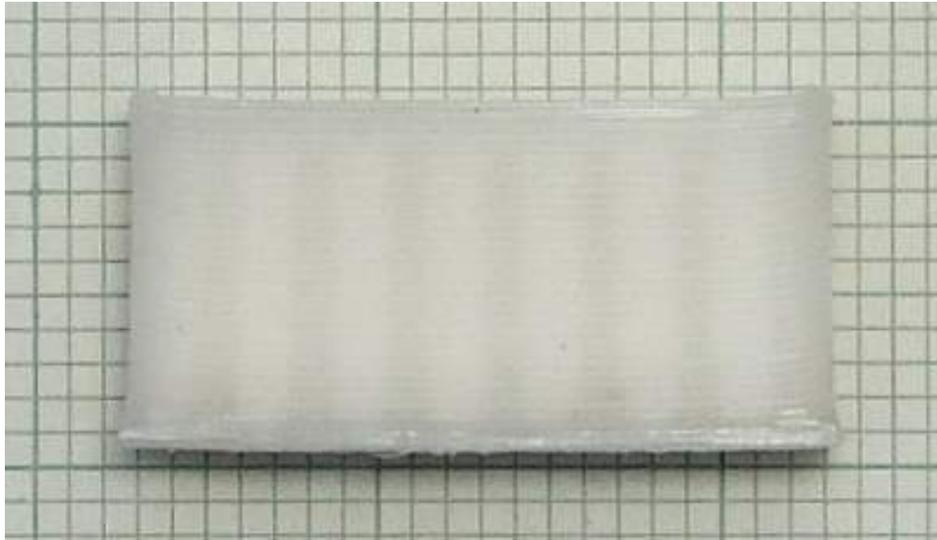
The ideal solution is probably a very big needle that locks onto the syringe. It doesn't need to be sharp but the 45° slant at the end is handy because it stops the end being blocked if you press it against the bottom of the object.

### Results

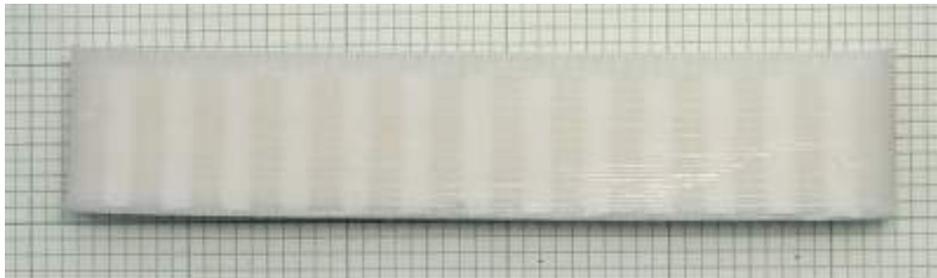
I left the objects on the bed overnight to make sure the PU was fully cured even though it sets in 15 minutes. The first object I made had a 50% fill and warped 0.36mm compared with 0.47mm without the PU injection.



Thinking that 50% fill leaves the PU fairly weak, I did another test at 25% fill. That gave 0.24mm warp, the lowest figure I have achieved yet for this shape.



I also tried a 100 x 10 x 20 mm test with 20% fill ratio. That gave about 50% less warping compared to the version without PU.



### Conclusions

A useful technique for reducing warping and reducing the build time of FDM objects. The main disadvantage is that FDM is one of the cleanest and safest fabrication techniques whereas injecting PU is messy and somewhat dangerous unless you wear protective gear.

I was disappointed not to get rid of the warping completely. Instead of alternating the horizontal and vertical fill patterns, several layers of one followed by several layers of the other might make the PU lattice stronger. Raising the PU to 50°C for a few hours is supposed to harden it further, so I could try removing the bed and putting it in a very low oven for a while. I have a Peltier effect 12V beer fridge which can be reversed and used as an oven, so that would be ideal.

Using a harder plastic like epoxy might work better but it may be too viscous to inject. I believe heating it reduces viscosity.

Reducing HDPE warping feels much like banging ones head against the wall so I will try PCL and ABS next for some light relief.

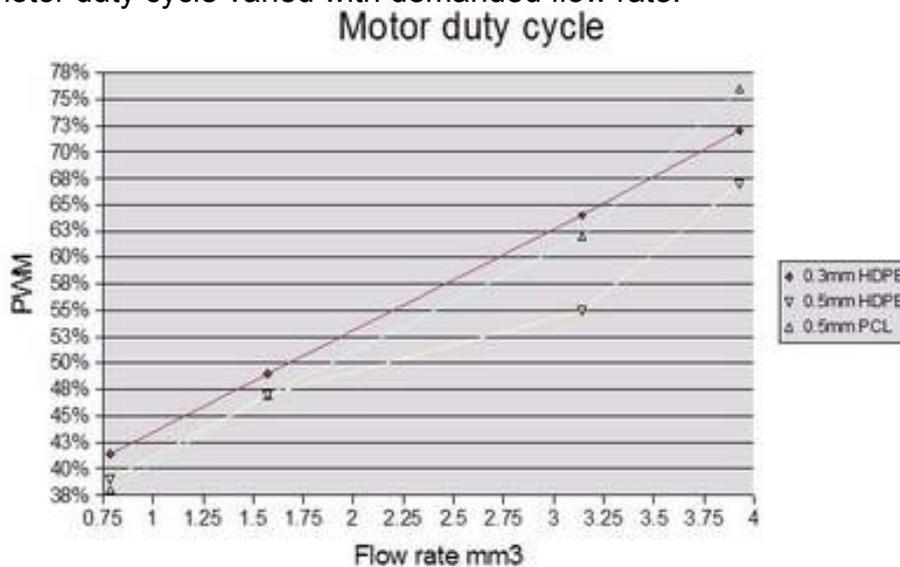
# Chalk and cheese

Friday, 28th March 2008 by Nophead

I was curious to see how polycaprolactone (PCL, trade name CAPA) compares to HDPE. I bought some from BitsFromBytes a while ago but have not had chance to try it yet. It is the plastic RepRap was designed for and there is plenty of evidence on the web that it does not warp like HDPE does.

The first test I did was to run the extruder at various flow rates and look at the filament diameter and the amount of motor power required. Although I think I only need to extrude at twice the melting point minus ambient (~100°C) to get it to stick to the next layer, the extruder seemed to struggle a bit so I did the tests at 140°C (measured at the nozzle).

This is how the motor duty cycle varied with demanded flow rate: -



The first surprise: although the torque required for PCL through a 0.5mm hole starts off lower than HDPE through 0.5mm, it actually rises faster with flow rate and ends up needing more torque than HDPE through a 0.3mm hole. This became a problem when I started to try to make objects because the clutch in the GM3 gearmotor kept slipping. It never slipped when I was extruding HDPE. I tried loosening the pump springs to the point where the filament started to slip and I tried backing off the flow rate but to no avail. I even replaced the GM3 in case the clutch was worn. I solved it by lubricating the filament with oil, a tip I got from Vik Olliver who found it necessary for PLA, the other RepRap plastic. I did that by passing it through a felt pad with a hole in the middle, with a few drops of 3 in 1 oil applied.

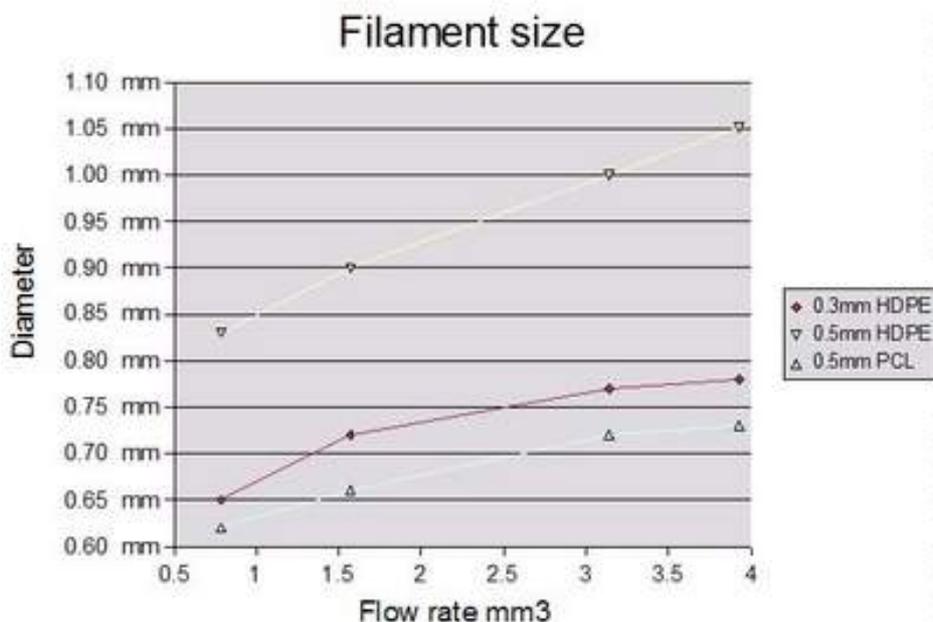


I found the felt disc in the road, I have no idea what it is, but I thought it might come in handy someday. If anybody recognises what it is please let me know.

The oil is very effective, a few drops lasts for many hours. Previously I was using PTFE spray to lubricate the pump for HDPE but that required opening the extruder occasionally.

The amount of spring pressure required for PCL is much less than HDPE, presumably because it is much softer so less force is required to make the screw bite.

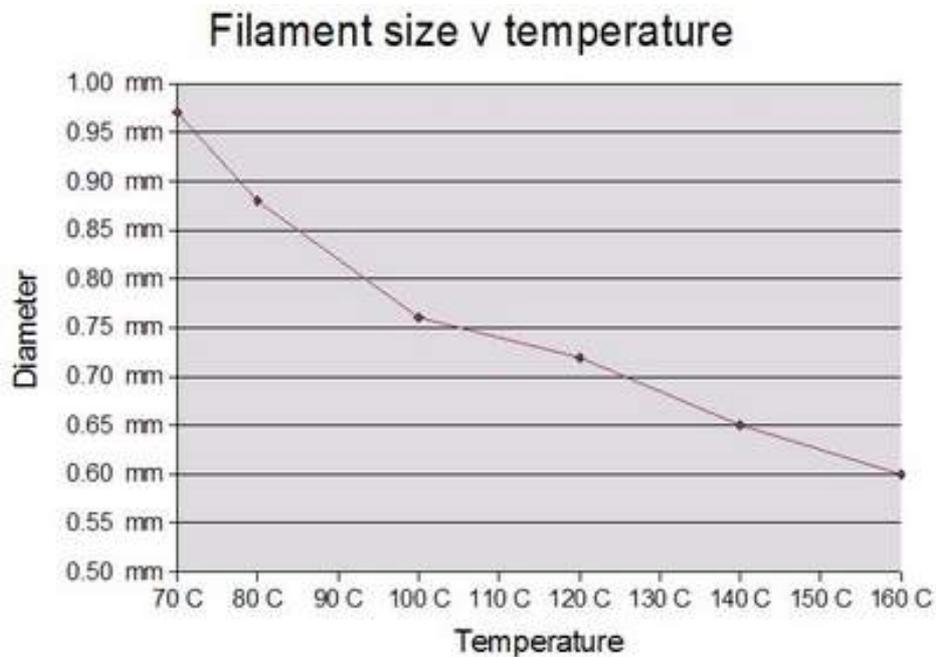
Next I measured the die swell: -



PCL has far less die swell than HDPE, such that PCL filament from a 0.5mm hole is actually

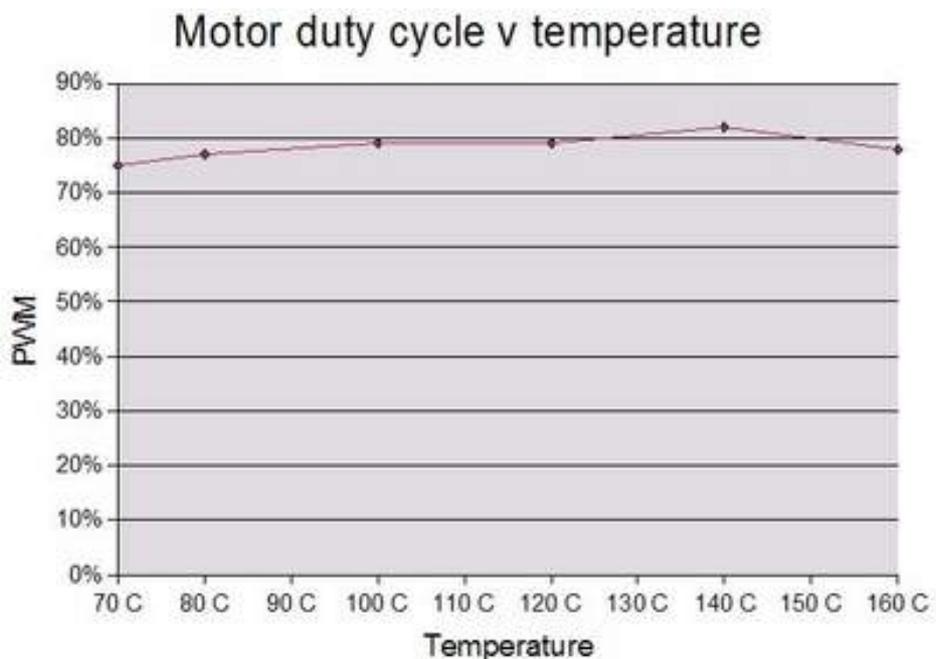
smaller than HDPE from a 0.3mm hole. Reducing the hole size to get smaller filament gives diminishing returns because the die swell as a percentage goes up with a small hole.

I also looked at how motor torque and die swell are affected by temperature. Once I had fixed the clutch slipping problem by lubricating the filament I had no problem extruding at low temperatures.



Quite a big variation in die swell indicating the viscosity changes a lot over this temperature range. This is also obvious looking at the filament. In fact some of the reason why it gets thinner at high temperature is that it is so runny that gravity probably stretches it. That may account for the inflection in the graph, or it may just be measurement error.

The next graph was another surprise: motor duty cycle plotted against temperature: -

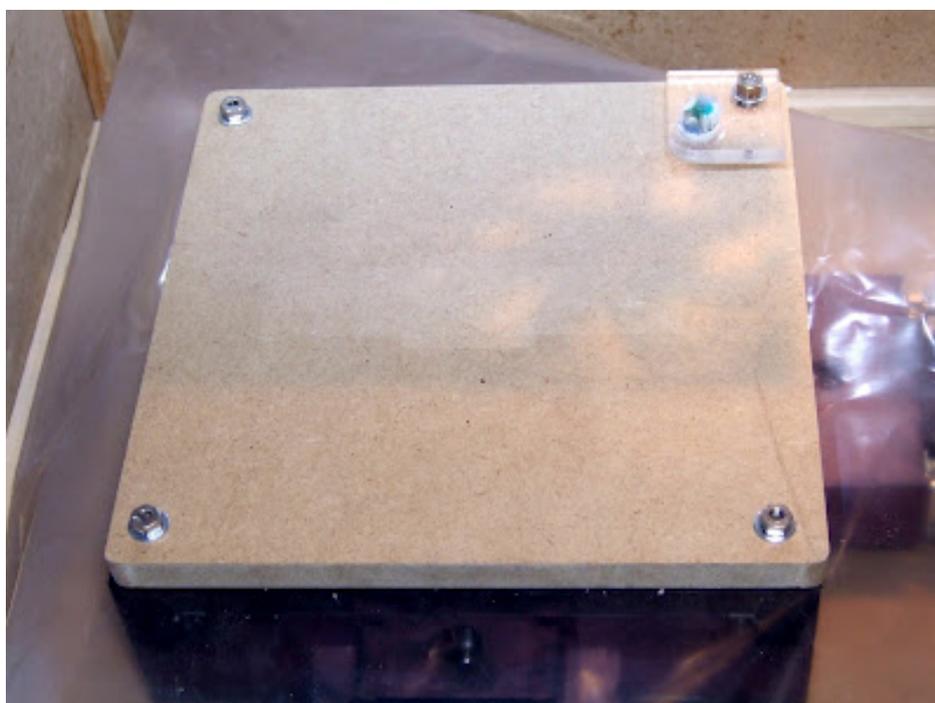


This is essentially flat, the slight rise is probably due to the motor windings getting warm, increasing their resistance and thus lowering its torque. The 160°C reading was taken after the motor had had time to cool down again. This is a good illustration of why a shaft encoder is necessary to control the feed rate.

So if the viscosity is changing, but it has no effect on the motor duty cycle, I have to conclude that most of the torque is required to overcome the friction in the filament guide. That also explains why more torque is required to extrude PCL than is required for HDPE, despite it being less viscous and requiring less spring force. If I rub my fingers over PCL it is obviously a lot less slippery than HDPE.

Having got the filament to extrude properly the next task was to get it to stick to the bed. I found that PCL does not stick to the PP board that I used for HDPE. I expect that is because it is too low a temperature to form a weld with PP.

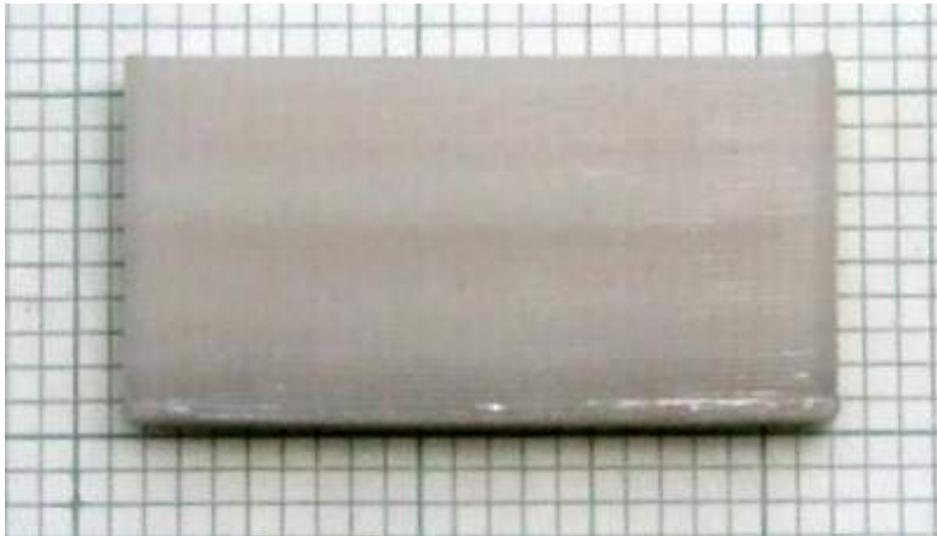
The RepRap Darwin machine use MDF so I decided to try that.



I assumed that I could dispense with the raft that I lay down for HDPE, but that was not the case. I found that PCL objects still curled away from the base, so I went back to using the raft. That holds the object flat but is a pain to trim off. For some reason it is easier to cut HDPE with scissors even though it is stronger. One downside of using MDF is that some of it comes off with the object so it is not completely reusable and it leaves wood fibers embedded in the base of the the raft. This is nowhere near as good as a polypropylene bed is with HDPE. That peels away undamaged and leaves no trace on the object. I think I need to do some more experiments to find a similar solution for PCL.

The first test shape I made came out very grey. It must have picked up some contamination in the extruder but the only thing that should have been in it was left over HDPE. Perhaps for some

reason white HDPE plus white PCL makes a grey plastic.

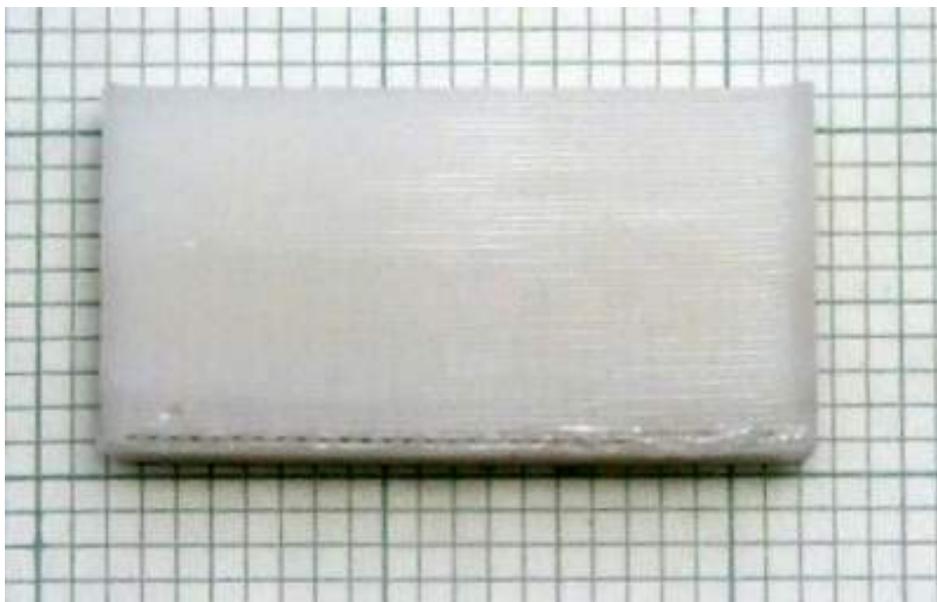


It was very flat to start with but over a few days it has warped slightly. The corners are lifted about 0.21mm compared to 0.53mm for a 100% filled HDPE block. That is also better than my polyurethane filled 25% HDPE block which had 0.25mm warping.

I think the reason PCL shrinkage is so much less is that although it melts at 60°C, it doesn't harden again until it is around 40°C. That means after setting it only cools a further 20°C back to room temperature. In contrast HDPE probably goes hard around 120°C so it cools a further 100° after that. Even if they had the same thermal expansion coefficient, PCL would shrink five times less.

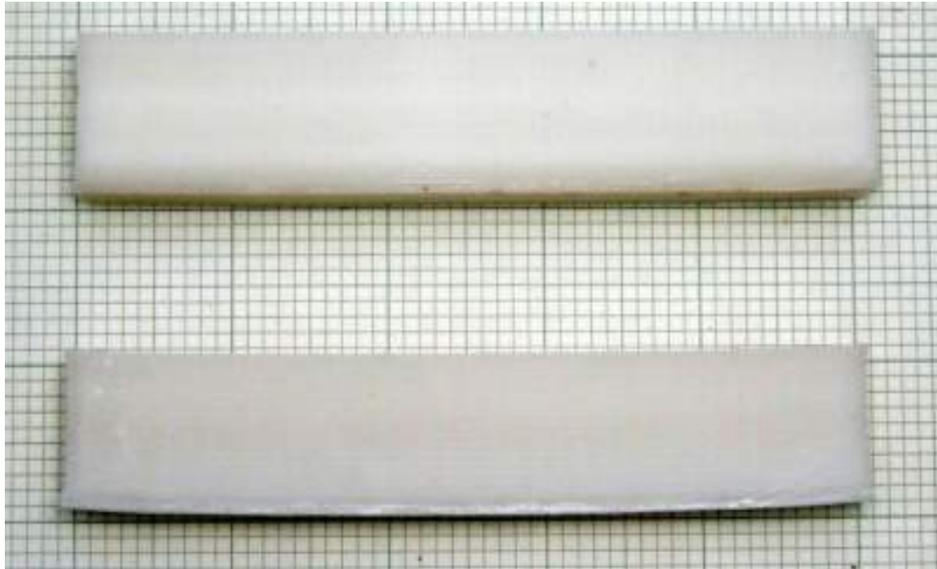
I did the first test at 8 mm/s because that is as fast as I could go with HDPE with my current nozzle. However, I found that I can go at 16mm/s again with PCL. I have a fan running continuously to cool the object because otherwise PCL takes for ever to set.

I made a second block and that came out white: -



It was extruded at 100°C, 0.5mm filament at 16mm/s, 0.4mm layer height, 0.6mm pitch. The reason for having the height so much less than the pitch with HDPE was that the object shrinks in height while it is being built, otherwise the nozzle ends up extruding into fresh air. Perhaps with PCL I can get away with a smaller filament aspect ratio.

Here is a longer test piece with a 25% fill HDPE equivalent underneath for comparison: -



The PCL shrinks far less but at 100% fill is not as strong as the HDPE at 25% fill. I can also make 25% filled PCL objects but they are very flexible. Presumably PU injection would work with PCL as well and get the strength back.

The brush that I use to wipe the nozzle does not work as well with PCL. With HDPE any bits left stuck to the brush get knocked off on the next wipe cycle. With PCL they get picked up again by the nozzle on the next pass. I need to go back to using a knife I think, as shown [here](#).

My acorn nut nozzle didn't work very well with HDPE compared to the one piece nozzle I used before, but it works much better with PCL. I get less extruder overrun and I can extrude quickly without the filament snapping.

PCL filament is much more compliant so the minimum corner radius is less and definition is generally much better. Some of this may be due to being able to run my fan again. I found that it improved HDPE definition but it pushes the heater temperature up above the point where the PTFE insulator goes soft.

So to summarise:

HDPE:

- Rigid.
- Cheap.

- Readily available.
- Handles high temperatures.
- Shrinks a lot leading to warping.
- High die swell.

- Doesn't stick to anything.

PCL:

- Springy.
- Expensive.
- Hard to get hold of in filament form.
- Doesn't handle high temperatures.
- Shrinks less leading to less warping.
- More compliant leading to better corner definition.
- Low die swell.

- Sticks to far more things.
- Has green credentials.

PCL seems better in all aspects that affect making accurate objects. HDPE is better in all other respects.

HDPE seems to push the extruder temperature wise and PCL seems to push it torque wise. I think a stainless steel barreled extruder with a PTFE lined filament guide will solve these problems.

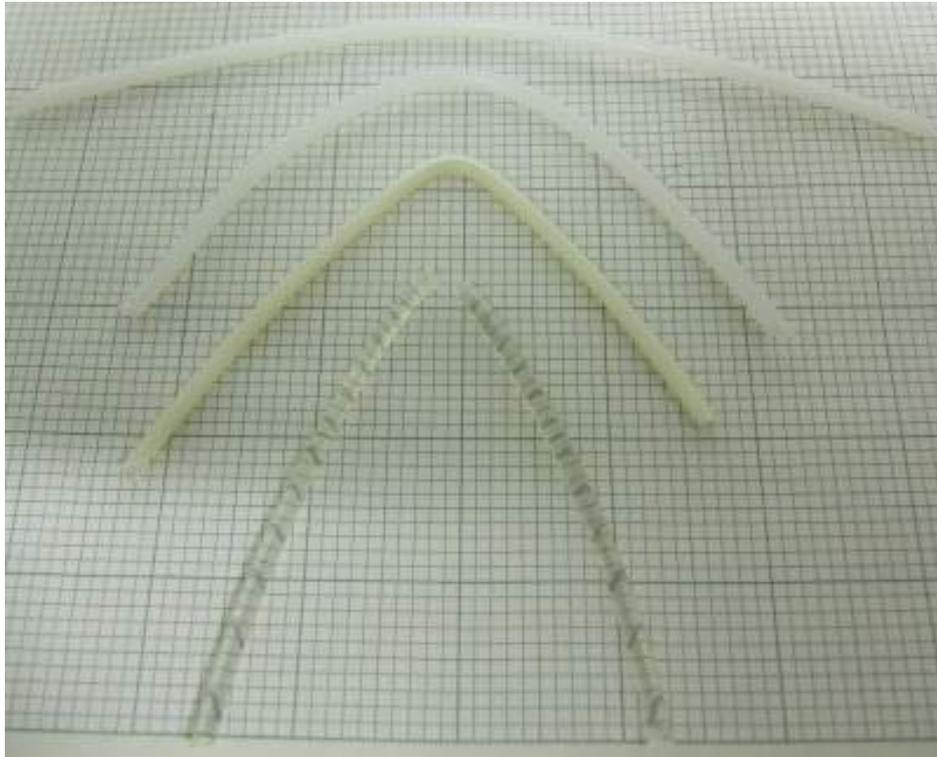
The PCL results look easily accurate enough to make the Darwin parts so I need to hook up my machine with the host software and start churning them out. The HDPE results are probably good enough for some parts and probably beneficial for motor couplings and mountings which get hotter than 60°C.

Before that I will have a go with ABS and then do some more work on my high temperature extruder design.

# ABSolution

Friday, 4th April 2008 by Nophead

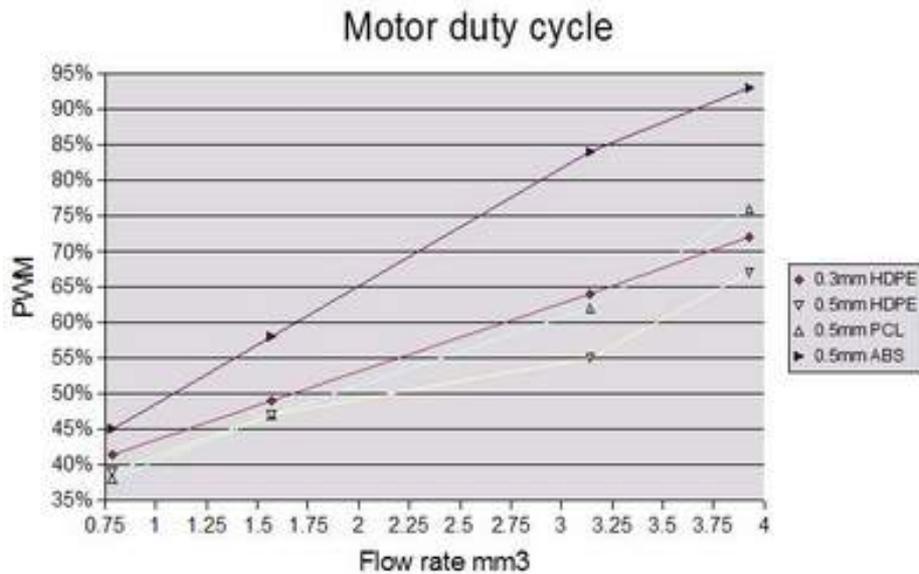
I have been testing Acrylonitrile butadiene styrene (ABS) in the RepRap extruder and I have to say it works rather well. It is surprising how different each plastic I try is. For example, if I fold a short piece of filament double and let it go this is what happens :-



PCL is rubbery and springs back almost straight, HDPE is a lot less springy. ABS bruises when bent sharply and is a more opaque cream colour rather than white. PLA is transparent like glass and breaks when bent through a small radius. The progression from top to bottom is from rubbery to brittle. I think the reason for this is that ABS and PLA are below their glass transition ( $T_g$ ) at room temperature, whereas with PCL and HDPE their  $T_g$  is well below  $0^{\circ}\text{C}$ .

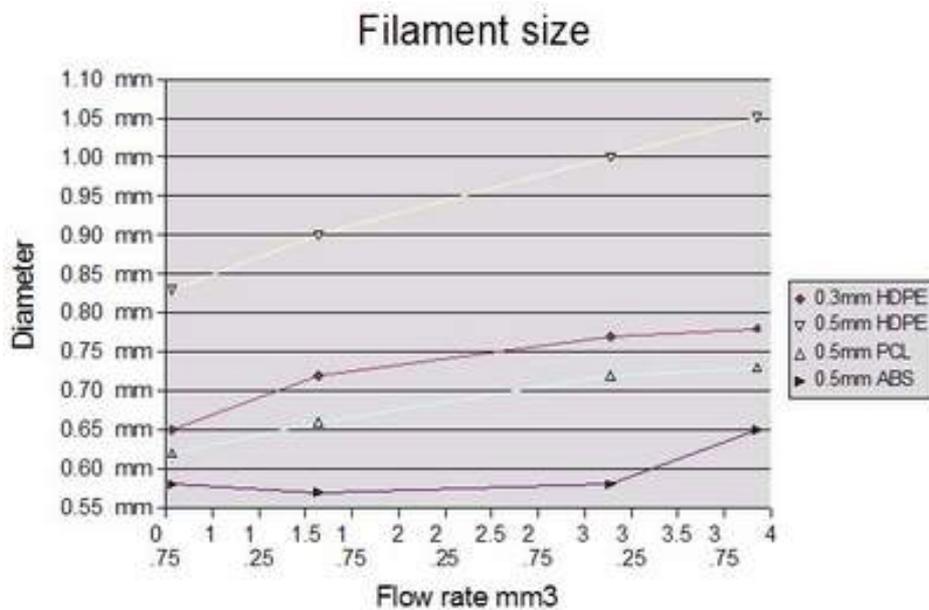
I have a bit of a routine now for getting my machine working with new plastics. First I look at the extruder performance at different flow rates and temperatures. Then I have to experiment to find a bed material it will stick to. After that I make test blocks to fine tune the temperatures and find the best speed and filament diameter to build with. Finally I look at the warping with different infill densities.

So here is the flow rate versus motor duty cycle extruding at  $190^{\circ}\text{C}$  measured at the nozzle (the other plastics are at different temperatures):-

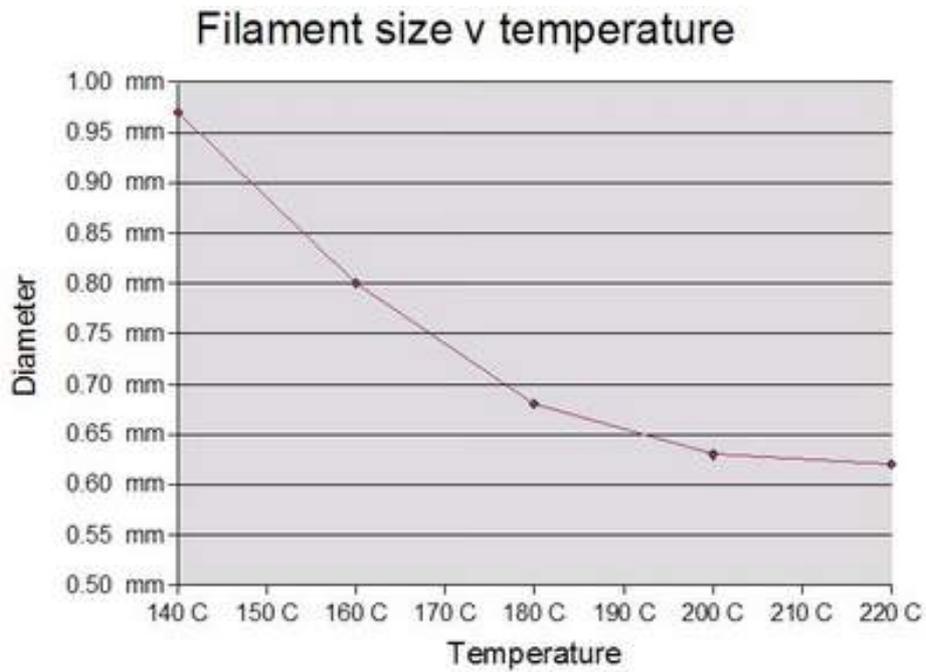


As you can see ABS works the motor harder. Part of this is due to the fact that it has to run faster (for the same flow rate) as the ABS filament I have is only 2.75mm rather than 3mm. However, I think that it is due mainly to the increased force and friction required to cut the thread in the pump. At first I had a lot of problems with the GM3 motor's clutch slipping. I got it working reliably by loosening the top springs and just tightening the bottoms ones. I also have the filament running through a felt washer soaked in oil, which I had to add when doing PCL.

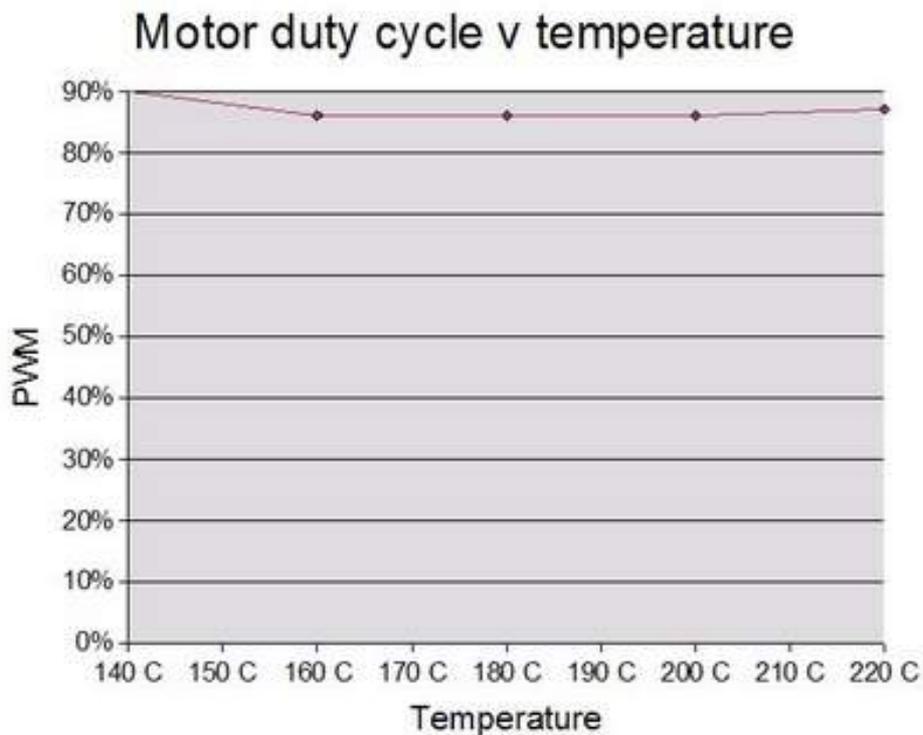
Here is how the filament diameter varies with flow rate :-



ABS has much lower die swell than HDPE and is quite a bit better than PCL. That makes it good for extruding fine filaments at high speed.



I think the graph above shows that the viscosity increases a lot as the temperature drops but the motor duty cycle remains pretty constant showing that most of the torque is used overcoming friction in the pump.



I tried using PP and MDF as bed materials but ABS does not want to stick to them. Unlike PCL which stays molten for a very long time, ABS filament sets soon after leaving the nozzle. PCL and HDPE turn transparent when they are molten but ABS does not. I think its specific heat capacity is quite low compared to HDPE so the workpiece cools quite quickly and I can get away without a fan.

The best material I have found for a bed is plastic laminated board. My wife bought me a big sheet of it for 10p when I was experimenting with HDPE. It was cheap because it was scrap advertising material. She was disappointed when HDPE did not stick to it, but is made up now that I have found a use for it. I think possibly it works because the thin plastic lamination is actually polystyrene.



I can extrude ABS on to it and it sticks well enough without needing a raft. To remove it I cut the lamination around it with a penknife and pull the surface off. I can then peel the lamination off the base of the object leaving a clean finish. It works well but I don't know where to get any more and it is single use although you can use both sides.



It is good not to need a raft because while I can remove an HDPE raft with scissors or a sharp knife, ABS 1mm thick is too hard to cut off easily.

My theory about welding temperatures is that you need to extrude at least twice the melting point (105°C) minus ambient. That works out at 190°C. In practice I needed to go a bit hotter to get a satisfactory bond between the layers at high speed. I settled on 220°C for the first layer and 200°C for the rest of the object.

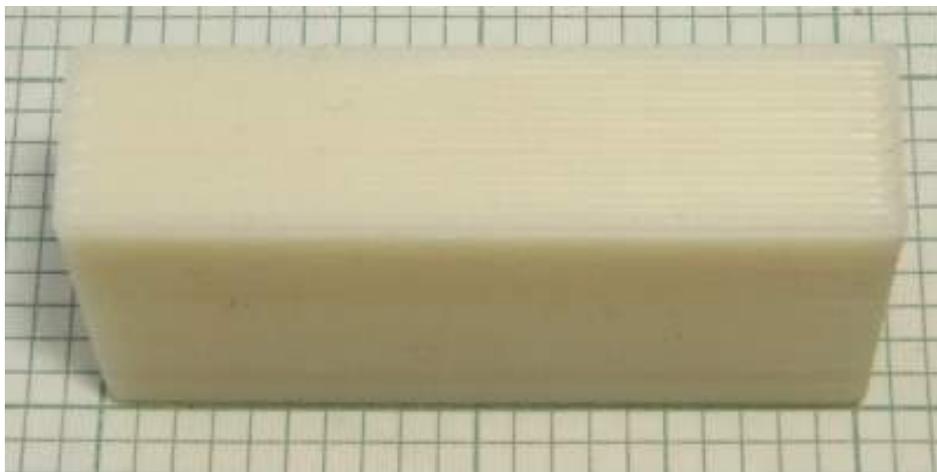
Layer bonding can be quite variable with ABS. It is easy to make objects which can be peeled apart again. I think this is because even at 220°C ABS is quite paste like and less fluid than the other plastics are at their critical weld temperature. That makes the filament contact points very tangential and so smaller. Plastics that are more fluid slump and get a bigger contact area, hence a stronger weld. Also, the time the plastic is in contact and above the melting point determines the amount of fusion. I think if I spend some time on this (and with the other plastics) I will be able to use plastics as their own support material for making overhangs. The layer height will be crucial to making this work so it will have to wait until I have replaced the PTFE insulator with stainless steel.

Here is my standard warp test shape: 40 x 10 x 20mm block made with 0.5mm filament at 16mm/s, layer height 0.4mm, filament pitch 0.6mm: -

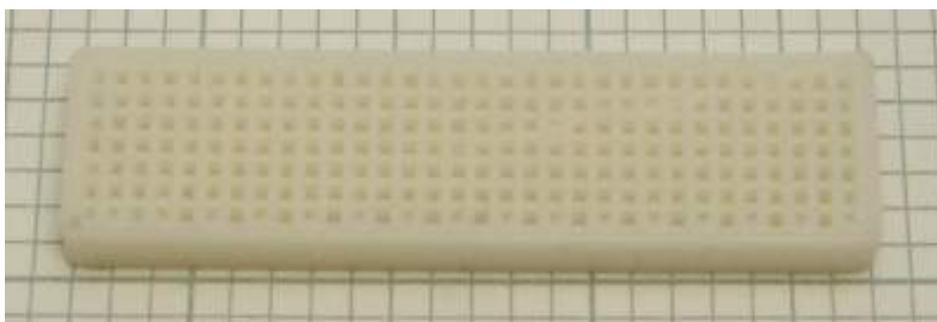


The warping figure I got after leaving it a few days was 0.38mm compared to 0.53mm for 100% HDPE and 0.21mm for 100% PCL. 50% filled ABS gives a figure of 0.15mm which is the lowest I have measured yet and ABS is still very strong at densities less than that, whereas PCL is not. Also, this was without a raft which gives worse figures for PCL and ridiculous warping for HDPE.

The filament is very soft and compliant when it is molten, with no spring in it, so it goes where the head leads it and produces good definition. Here is a top view showing how accurate the corners and infill are: -



Here is a 50% infill pattern: -



This is very accurate compared to the same pattern in HDPE shown [here](#). 25% fill is also very good and the object remains strong: -



For some reason my 9M pixel camera doesn't like taking close ups of white things.

When I was extruding thick rafts I noticed some bubbling of the surface. I think this is due to absorbed moisture turning to steam because ABS has ten times more water absorption than HDPE. Oddly, it does not happen when extruding the object so is not a problem, at least with the current weather conditions.

ABS smells a little when it is hot but not enough to be objectionable.

My acorn nut nozzle, with the very shallow exit hole, is very incontinent with ABS as it was with HDPE but not with PCL. This means that even though I wipe it clean with the toothbrush it has extruded another few millimeters by the time it gets to where it has to start the object. The problem with that is that it sets so fast it is solid when it meets the table so will not stick and stops the following filament sticking. I am hoping the latest nozzle design will fix that.

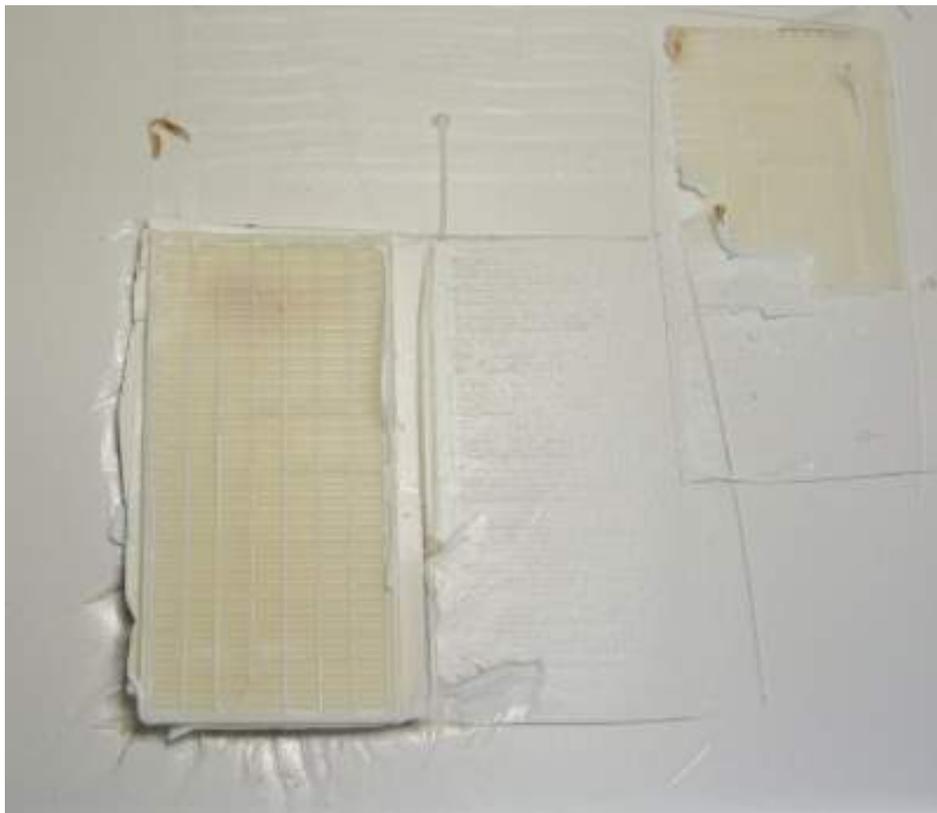
On to the same test with PLA before I alter the extruder.

# Stuck fast

Sunday, 6th April 2008 by Nophead

In the previous article I said I could use both sides of the advertising board as bed material. Well the back of the board is a thick layer of a leathery sort of plastic, I think it may be PVC. I can certainly deposit ABS onto it, but it sticks so well and is so tough I found it completely impossible to remove.

The front of the board has a very thin layer of plastic with paper behind. That may also be PVC, but being so much thinner is easy to peel away.



Interesting that ABS appears to bond so well to PVC, if that is what it is.

# Wear and tear

Sunday, 6th April 2008 by Nophead

Half way through my evaluation of PCL the extruder's flexible drive coupling started to break up again. When I moved to ABS that was the final straw: -



The first one I made was only 2.5mm cable. This was a 3mm one from [BitsFromBytes](#). I replaced it with some 3.2mm cable from B&Q. I drilled the hole out to 3.3mm so it is a snug fit. I also soldered it while it was held in alignment by my lathe so it is very straight.

I think the force required to bend a cable goes up with the fourth power of its diameter so this one is considerably stiffer. Possibly some of the motor torque is wasted in flexing it.

The good thing about the shaft I got from BitsFromBytes is that it is solderable, so it makes it easy to replace. My original shaft was stainless steel so I had to glue the cable in with JB Weld, making it harder to replace.

My next extruder will be direct drive!

I also wore out the brushes on a second GM3 gearmotor. I replaced it with a 12V version which has to be ordered by phone from [Solarbotics](#) in Canada. It looks the same except that it has a

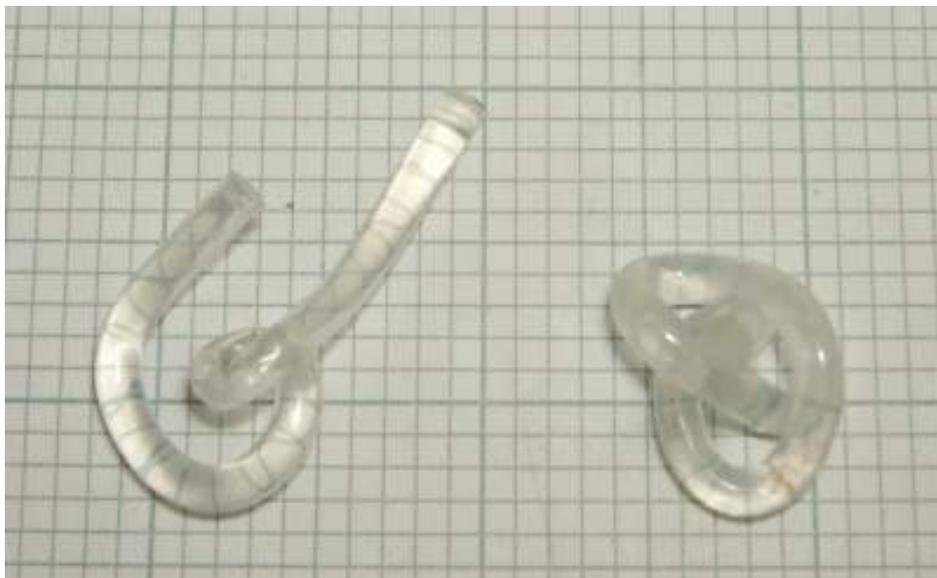
black end cap instead of a white one. It runs a bit quieter but I don't know if it will last any longer. As you would expect the coil resistance is higher so the current through the brushes will be lower.

# A day with PLA

Sunday, 6th April 2008 by Nophead

Adrian Bower has kindly given me a small sample of polylactic acid (PLA) filament to evaluate and some parts to make the new geared extruder are on their way. Being a bit too impatient I decided to try extruding it with my current extruder.

Each polymer I have tried so far (HDPE, PCL and ABS) has had very different characteristics and PLA is very different again. At room temperature it is very hard and brittle and is completely transparent. At somewhere between 50-80°C it has a glass transition temperature above which it becomes a rubbery jelly. If you put it in boiling water and then pick it out with tongs you can bend it as much as you want and when it cools it will set in that shape. These are the two bits of 3mm filament I showed earlier when I had bent a 150mm piece double and it snapped :-



After dipping them in boiling water I could tie knots in them but I had to be quick because it hardens in seconds. If I return them to boiling water they untie themselves and return to being a straight rod.

PLA melts at about 175°C, the highest of all the polymers I have tried so far, where it transitions from jelly to a liquid with the consistency of a thin syrup. If you extrude it quickly into mid air it sets almost instantly and forms a filament, but if you extrude it slowly it forms drops that drip from the nozzle like water from a tap, but are solid when they hit the deck. Very different from HDPE and ABS which extrude more like a paste. Like PCL, PLA is sticky when molten so it sticks to MDF quite well, unlike HDPE and ABS.

Getting it to extrude from the original extruder is next to impossible, I really should have waited for the gears. The problem is that the extruder pumps the filament by cutting a thread into it. PLA is so hard that it needs an enormous force to press the thread into its surface. That is no problem with the springs I have, but it also seems to have a high coefficient of friction, so the torque required to

turn the thread is then too much for the GM3 gearmotor and its clutch slips.

Recently I had an idea to cut the torque requirement by shortening the thread. The reasoning goes like this: -

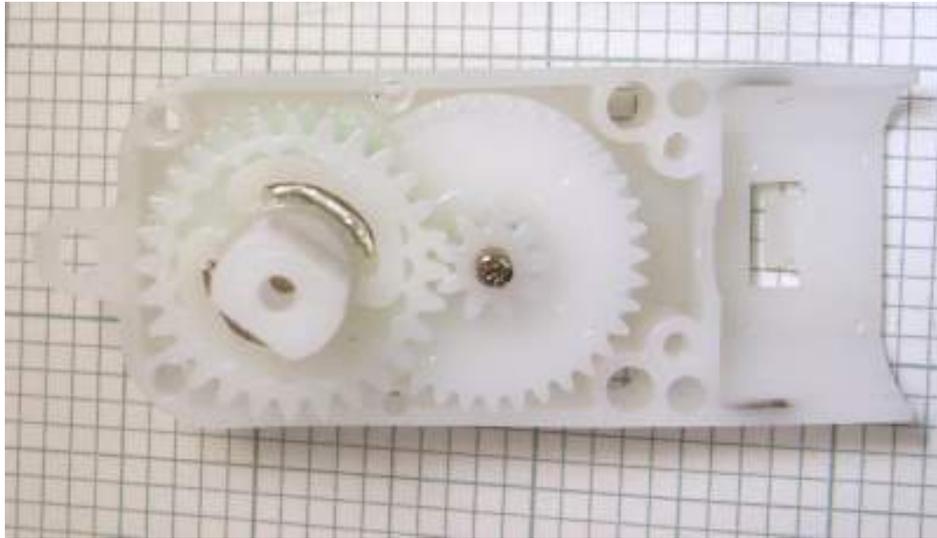
A substantial part or perhaps most of the force required to push the polymer is not the extrusion pressure but the lateral friction of pushing the filament through the filament guide and the tangential friction of cutting the thread. Both of these are equal to the respective coefficients of friction multiplied by the force exerted by the springs. But the force required to achieve enough pressure to push the thread into the plastic must be proportional to the length of contact. So once you have enough thread to push the filament without shearing off, any more is counter productive. It requires more spring force, which creates more friction, which makes the filament harder to push, a vicious circle.

Ian Adkins put the theory to the test and reported he could still extrude PCL with only 7mm of thread. The motor current dropped from 240mA to 190mA. The no load current was 62mA so that indicates about a 50% reduction in torque required. Not being as brave as Ian, I reduced mine a bit less radically to start with. I roughly halved it: -



I used a couple of washers at the top set of screws to space the pump halves apart, to keep them parallel, and just tightened the bottom pair of springs. That did reduce the torque required but even with plenty of oil the GM3 clutch was still slipping. It is a good modification because you save two springs, hence two less adjustments, and the extruder is quicker to strip down and rebuild. Plus future versions of the pump can be made much shorter.

All the adverts for the GM3 say the clutch can easily be locked but don't say how. I opened the gearbox and found the clutch is inside the last gear wheel. I tried putting some bits of thick wire into it to stop the springy bits from compressing.



That worked for a while until one fell out. I thought they would be trapped by the lid but seemingly not. My next attempt was to stick them in with super glue. That worked but the clutch still slips somehow.

Another issue with PLA is that the filament likes to rotate in the pump. Other polymers do that as well, but if you hold them so they can't rotate they still extrude. With PLA, if you don't let it rotate it slows down the motor. Presumably by letting it turn it removes the tangential friction leaving only the sliding friction. The problem with letting it rotate is that I think it means the forward motion is less so the extrusion rate is not what it should be.

When the clutch slips it jumps one notch. Because my shaft encoder is on the output shaft the firmware makes up the difference. If it does not happen too often I still get the right volume extruded. It does however cause a shock wave which makes a blob in the extruded filament. I decided to try and make an object anyway with it slipping occasionally.

Because I only had 8m of filament I decided to try a sparse filled object first. That does not work with PLA because the unsupported filaments sag: -



However, this messy object has a perfectly flat base so shows some promise.

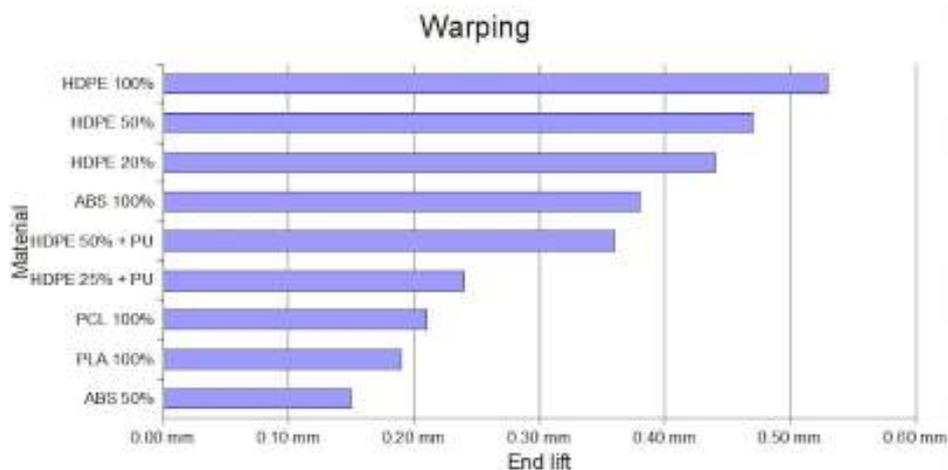
Next I tried a 100% filled block, extruded at 180°C (at the nozzle) 0.75mm filament at 8mm/s, layer height 0.6mm, pitch 0.9mm, fan on continuously. A bit slow and course compared to my other tests but I always start slow and move up in speed.



During this build the clutch started slipping once or twice per revolution causing the warty surface. Near the end it started slipping continuously so this is only about 18.5mm high rather than my standard 20mm test. Never the less, it only has 0.19mm warping after more than 24 hours making it the least warping yet for a solid object. Added to that it is probably the hardest material of the four.

PLA's main downside is the low temperature at which it goes soft, not much better than PCL, even though it has a much higher melting point. In this respect it is very like PVC which also has a high melting point and a glass transition around 80°C.

Here is my warped league: -



I think I can explain why plastics are good and bad for warping. It is simply how much they contract between the point they go solid and room temperature.

HDPE has a high freezing point and high thermal coefficient.  
ABS has a slightly lower freezing point and a low thermal coefficient.  
PCL has a very low freezing point.  
PLA has a glass transition point not much higher than room temperature.

If the object can be stuck to a rigid base while it is cooling then the warping is reduced.

My theory of needing to extrude at twice the melting point minus ambient certainly does not hold for PLA, otherwise I would need to extrude it at 330°C. I get very good bonding at 180°C. It may be that if I extrude very fast it would need to be hotter but I expect it would decompose at 330°C. It may be that the glass transition makes the theory invalid or maybe it is plain wrong. It does seem to be true for polymers which are paste like and not sticky, i.e. ABS and HDPE. PCL and PLA are both sticky when molten. I.e. they will stick to things like glue does whereas HDPE will only weld to things like itself. It has no adhesive quality.

I haven't entirely given up with making the non geared extruder work with PLA. The problem with the geared version is that it can't keep up with my extrusion speeds. I can try reducing the thread even more. I can try sharpening it as Vik Olliver has done. I can find a solution to locking the clutch. The motor does get quite hot so it probably won't last long. I do have three more to burn through before I find a better motor. They only seem to last a couple of weeks in my machine anyway.

# Locking the Solarbotics GM3 clutch

Monday, 7th April 2008 by Nophead

All the adverts for the Solarbotics GM3 gearmotor say the clutch can easily be locked but don't say how. I emailed them today and got a quick reply from Dan: -

Locking the clutch is actually very easy... we should make an effort to get the instructions on-line. All you have to do is glue the little plastic clutching mechanism in its cavity, but to ensure a good contact you should first wipe it out with rubbing alcohol to get the grease out, then score the surface up a bit with the tip of an Exacto knife and then you can use either super glue, model cement, or epoxy to lock it.

So that is what I shall try next to see if i can get it to extrude PLA without warts.

# Fantastic PLAstic

Tuesday, 8th April 2008 by Nophead

I have managed to get the GM3 to extrude PLA reliably with the following tweaks: -

- I locked the clutch as per Solarbotics [instructions](#).
- I lubricated the GM3 with silicon grease as per Adrian Bowers suggestion.
- I sharpened the thread a bit with a half round file following Vik Olliver's instructions.
- I spaced the top half of the pump slightly further apart with some thicker washers. That gives the thread a gentle lead in.
- Plenty of oil on the filament.
- I throttled back the flow rate to 3/4 of the rate I normally use ( $\pi \text{ mm}^3/\text{s}$ ).

The motor runs warm, but not alarmingly so. For some reason the filament is no longer rotating in the extruder.

My first attempt curled away from the MDF bed so I used 2mm balsa wood as Adrian has been using for PCL. That worked well so it's good that we can use it for both. I have yet to try it with HDPE and ABS.

I made my standard test block with 0.5mm filament extruded at 180°C (at the nozzle), layer height 0.4mm, pitch 0.6mm, fan on constantly. The results are excellent: very good filament compliance, i.e. sharp corners and flat sides, excellent layer bonding.

It is slightly more warped than my first test. That is probably because balsa is softer than MDF.



No warts on this one!

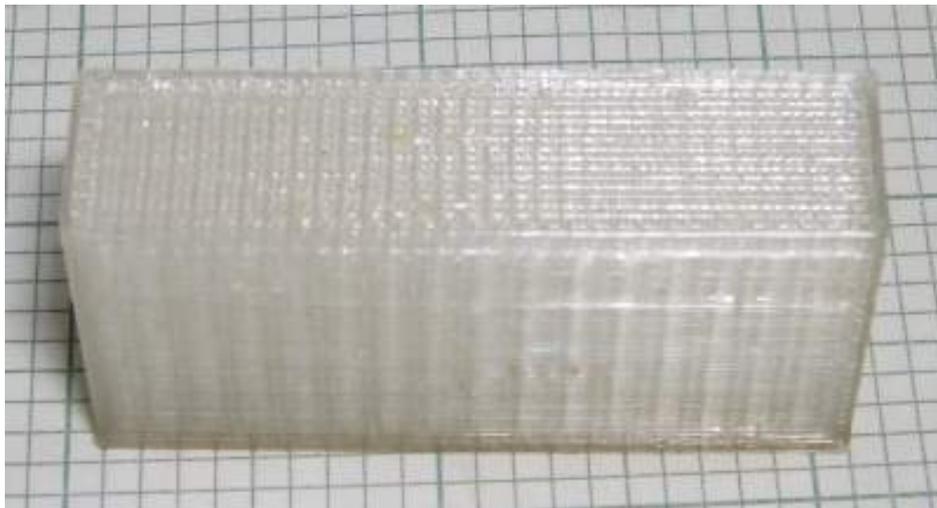
# More PLaying

Thursday, 10th April 2008 by Nophead

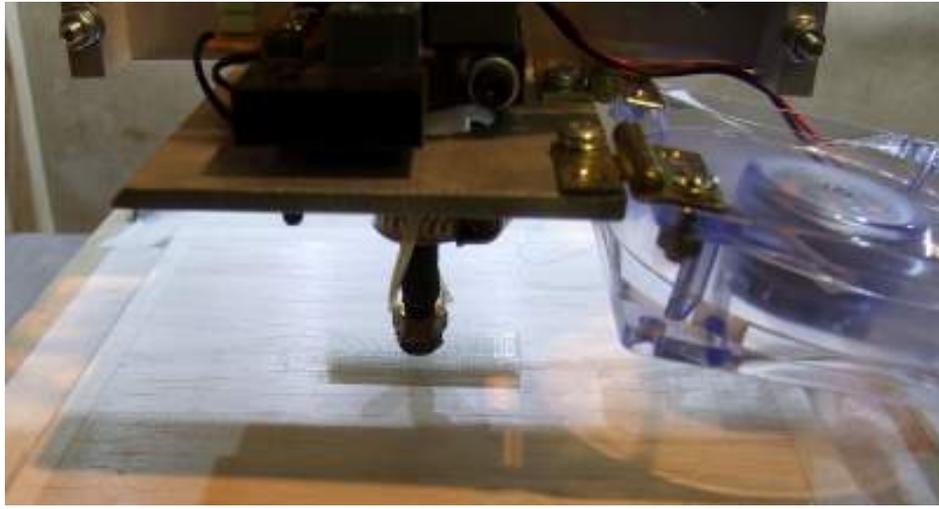
The tweaks I made to my extruder dramatically improved its ability to extrude PLA. I am not sure which one made all the difference or whether they are all needed. I can now extrude at my target 0.5mm filament 16mm/s with about 75% motor PWM duty cycle. That is less than I needed for ABS before the tweaks.

I can also extrude at lower temperatures. I think 180°C is a bit on the hot side as the plastic is very runny at the temperature. It will flow out of the extruder under gravity and has negative die swell. At 140°C it behaves more like the other plastics and swells to 0.6mm, which is very low.

In a previous article I stated that I could not make sparse filled objects because the filament slumped too much. With the reduction in temperature and increase in speed I now can. Here is a 50% filled block: -



It is still very strong. I expected the warping to be less but I have switched from MDF to balsa and I think that increased it. The balsa I have is only 2mm thick and was only stuck down with masking tape. I might try gluing two pieces back to back with the grains at right angles to get it stiffer.



So now with a slightly tweaked extruder I can do PCL, PLA and ABS at 0.5mm @ 16mm/s. I had to slow down for HDPE to prevent thermal damage to the extruder.

To get good definition at high speed I extrude with a fan running. The fan cools the nozzle which causes more heater power so the barrel temperature rises to the point where PTFE goes soft and the JB Weld turns to dust. PCL and PLA are no problem because the temperature is less. ABS does not seem to need the fan.

I plan to make a PTFE cover for the nozzle which will probably insulate it well enough and hopefully stop filament sticking to it and burning.

# Basket case

Thursday, 10th April 2008 by Nophead

I was using two old component spools to hold my feedstock, see [all-wound-up](#), but I don't have any more so now that I have four polymers I decided to give Vik Olliver's [design](#) a try. It has the advantage that you don't have to spool all the filament on, you can just drop in an open reel if that is how your filament comes.

This is my take on it: -



The uprights are 15x15mm aluminium angle. The beam across the top is a piece of 20x10mm channel. The bearing is a standard ball bearing and I reduced its internal diameter with a couple of bushes I had lying around. I then used a bolt with holes through the head as an axle. I found it in the road while I was on a walk wondering what to use. That is the third piece of HydraRaptor that I have picked up in the street.



The baskets are £4.21 in B&Q and have a plate in the bottom with a central hole just right for feeding the filament through. As the machine pulls the filament from the centre of the reel, the basket rotates to prevent it becoming twisted.

It works very well and has the advantage I can buy as many baskets as I have plastics and just take them on an off as needed.

It also allows the filament to rotate in the extruder but ironically, since I tweaked my extruder, PLA no longer feels the need to rotate. Presumably it rotates if the friction between the screw and the plastic is higher than between the plastic and the filament guide. I think that gives a clue to which of my tweaks made all the difference in reducing the extruder torque needed. I think it was adding the washers to space the top of the pump apart so that the screw bites in progressively and sharpening the screw thread.

# Python & Beans make object

Wednesday, 16th April 2008 by Nophead

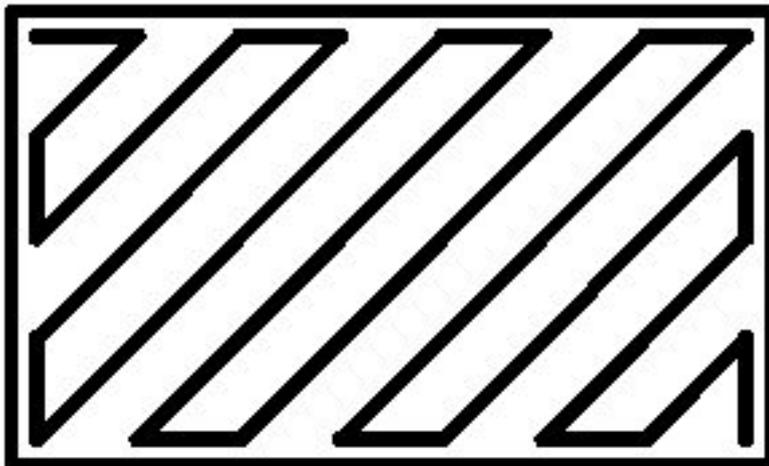
Having got bored of making rectangular blocks for months I decided it was time to hook up my machine to the RepRap host software so that I could make arbitrary 3D objects from STL files. My original plan was to hack the host code to replace the serial comms with Ethernet and cope with the differences of my machine from the RepRap Darwin. Zach Smith added a G code back end so I decided to just add a G code parser into my Python to save me having to modify the host.

In the meantime Enrique Perez published a plug-in script called Skeinforge.bsh for ArtOfIllusion that also converts 3D objects to G code extruder paths. It is written in the Beanshell script language, which is Java like. I decided to try both approaches, as in theory a G code parser would allow me to use either.

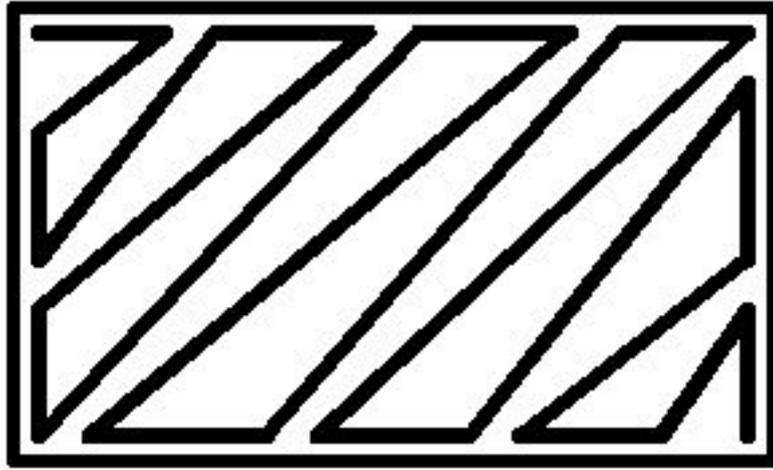
Enrique posted some new scripts that process G code and drive the RepRap hardware using a Python SNAP protocol driver written by greenarrow, so I didn't even need to think about writing a G code parser, I just cut and pasted a few lines from Enrique's.

Before letting it drive my machine I thought it would be a good idea to look at the paths on screen. I knocked up a little script which used my HydraRaptor simulator to draw them. The script is just a few lines of Python that use TkInter.

It was soon apparent that Enrique's code had a bug that left off some of the outline, but apart from that it looked very promising because it has the ability to do sparse infill. That speeds up building objects, saves plastic and reduces warping so it is very worth while. Not only that, it had a novel infill pattern. Instead of parallel lines like this: -



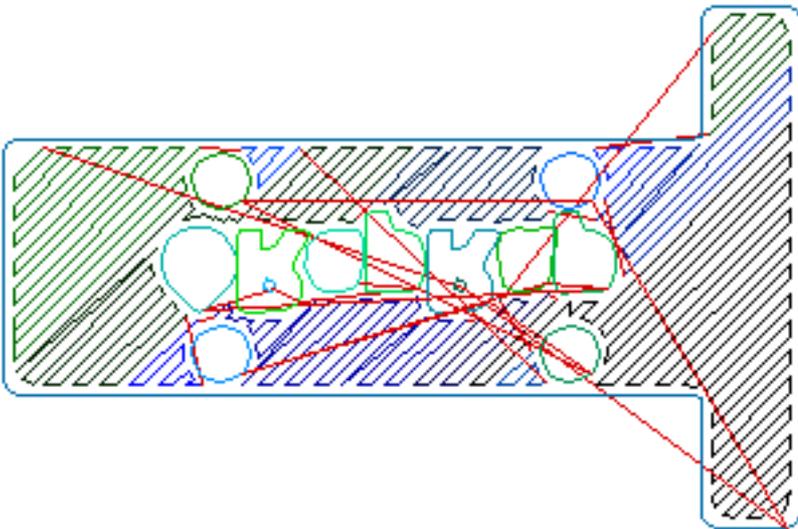
He moves the ends together so that the outer wall is stronger: -



This looks like a good idea because it makes the outer wall effectively two layers thick but probably gives a bit less warping than a second continuous layer would give.

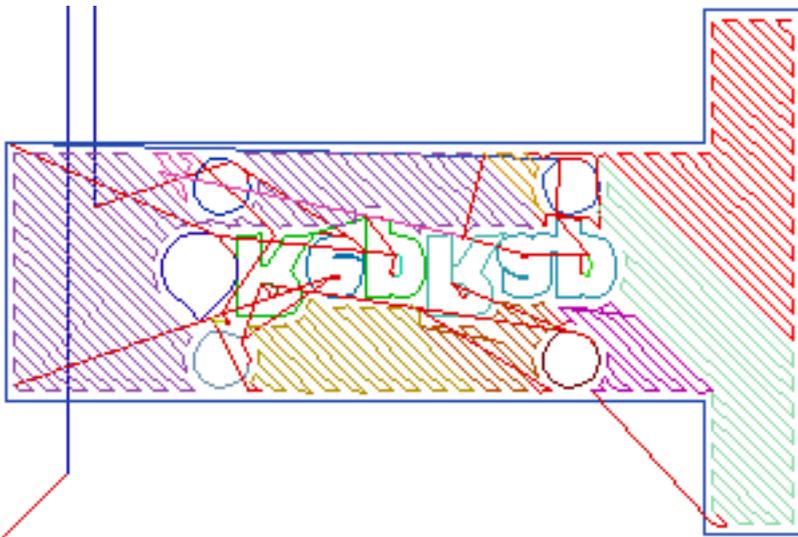
In order to communicate the results to the forums I came up with the idea of making an animated GIF showing all the layers in sequence. This turned out to be very easy using Google and Python. The Python Image Library (PIL) can make GIF files and I found a script called gifmaker.py which takes a list of images and uses PIL to calculate the deltas and write out an animated GIF.

Enrique fixed the bug very quickly, here is the sliced extruder pump body: -



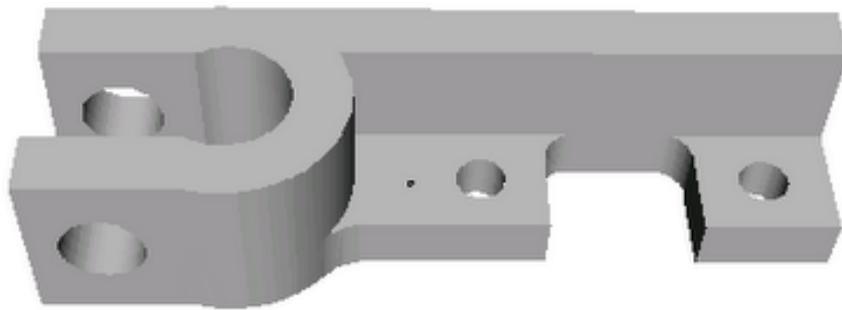
The red lines are moves without filament flowing (ideally) and the each new section of filament is a different colour.

And here is the same object sliced by the reprop host :-



A side effect of Enrique's algorithm is that the corners get rounded, however I don't think that matters too much because the filament has a minimum bend radius anyway. The main downside is that beanshell script is very slow, so it takes longer to slice than it does to extrude at the moment. A faster PC will probably sort that.

The first object I tried to make was this opto mounting bracket from the RepRap Darwin: -



I choose it because it is small, so does not take too long, but reasonably complex with a horizontal hole. Here is the sliced path from Enrique's script: -



Image not found.

And here is my first attempt at making it: -



This is PCL extruded onto MDF, 0.625mm filament extruded at 10mm/s with the fan on, no interlayer pauses.

A bit hairy due to the extruder not being able to stop the filament flow quickly, but I was quite pleased with it for a first attempt. It is too tall due to a bug in my code and its not the latest version, which has teardrop shaped holes to make the overhangs less than 45°.

Here it is cleaned up a bit: -



It is 50% filled which is probably not appropriate for this size object in PLA but that part is fully functional I think.

Enrique was pleased to see it as he doesn't have a machine to test his code with. A perfect partnership, he writes all the hard bits in beanshell script and I write the easy stuff in Python!

# Fun with Python and G code

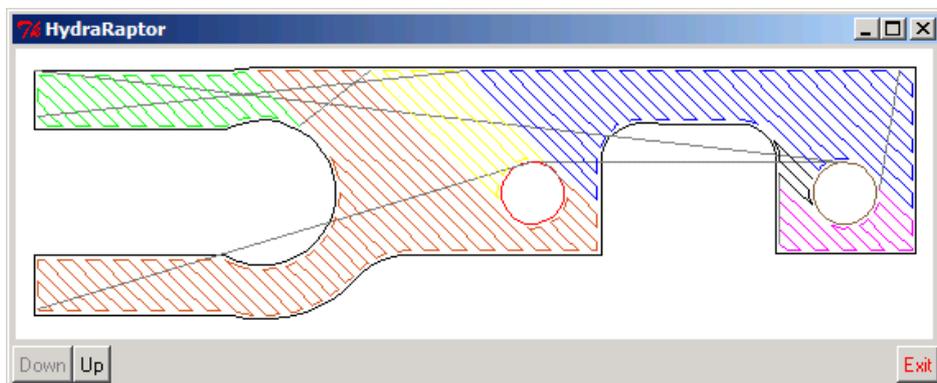
Monday, 21st April 2008 by Nophead

The current RepRap host software is a monolithic Java program that imports STL files, lets you place the objects to be made on the table, slices and dices them and controls the machine.

In my opinion the slice and dice code should be a separate program from the machine controller. Its inputs should be the 3D model in STL format plus the filament dimensions and the output should be an XML file with extruder paths grouped into layers, outlines and infills. The machine controller then reads the XML and controls the speed, temperature, fan, nozzle wiping, cooling delays, etc, according to the selected material and the machine characteristics. A third layer of software should be the communication protocol to the slave device, e.g. SNAP or G code over serial, USB, Ethernet, etc.

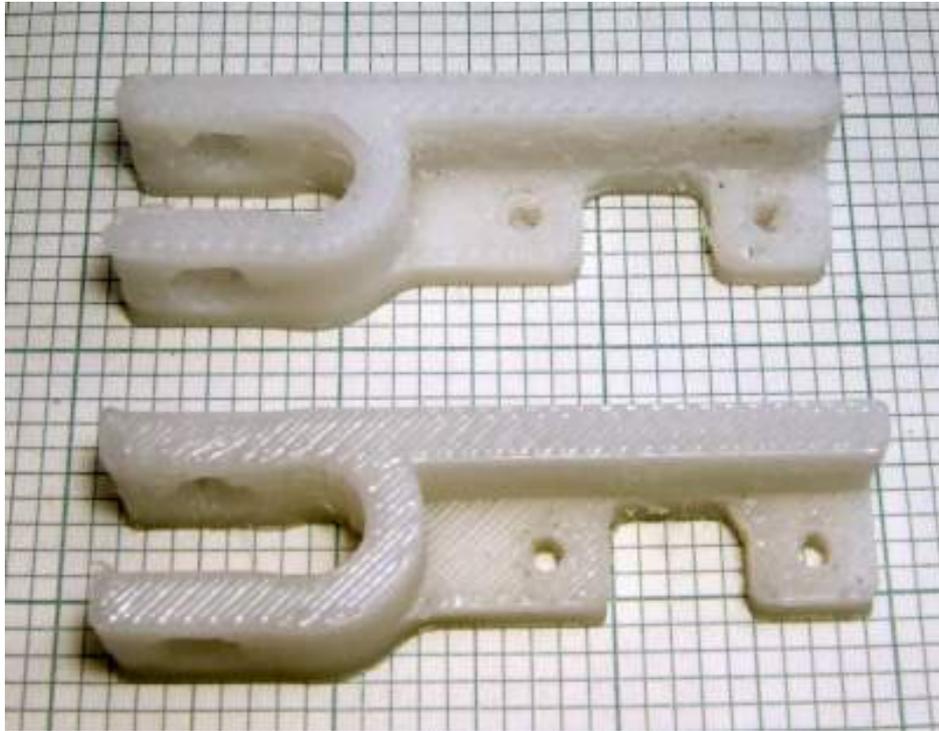
I have moved a little way towards that model by making my machine accept G code from the RepRap host or Enrique's Skeinforge script. I throw away most of the G codes, looking at just enough to build an internal representation of the extruder path. This is simply a list of layers, which are lists of threads, which are lists of points. From that information I can control my machine, make animated GIFs or preview the paths in a GUI. All of this is trivial in Python.

Here is my first cut at the preview GUI: -



The preview shown is from G code generated by the RepRap host, and here is the object it made:

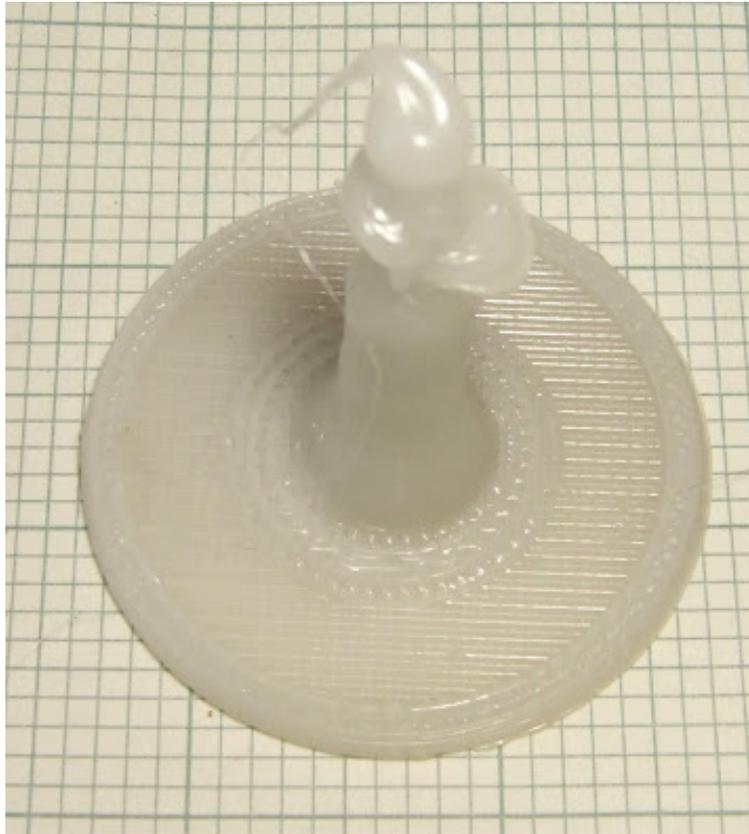
-



Behind is the same object made from G code generated by Skeinforge.bsh. The RepRap one has sharper corners and the infill is a bit better but the Skeinforge one is faster to produce because it has sparse infill.

Here is a video of it being made: -

Here is my first attempt to make Vik Olliver's shot glass: -



When it got to the stem the fan could not get the heat away faster than it was arriving and the whole thing became a molten mass. I fixed that by slowing down the extruder to 8mm/s when the layer gets small: -



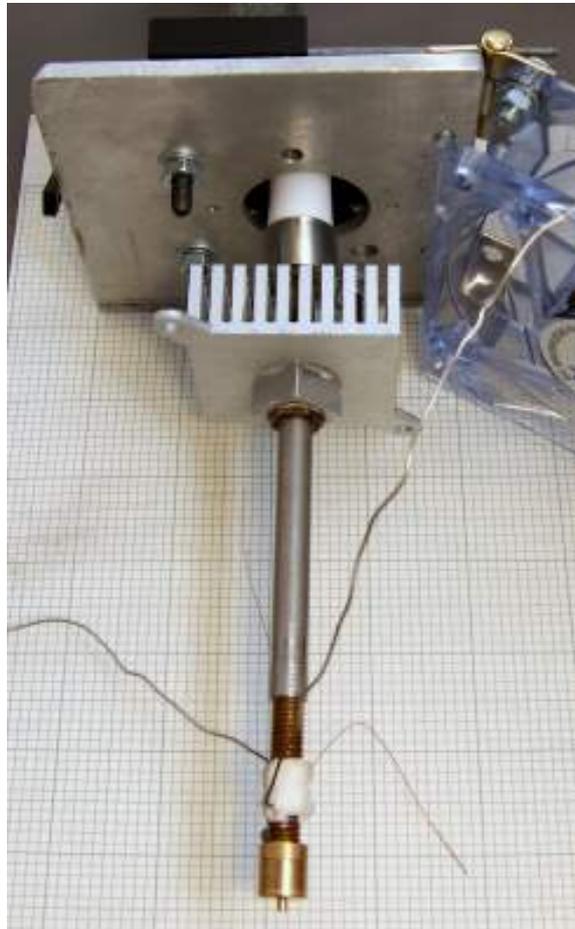
It took five hours to process with Skeinforge and an hour and a half to build. I couldn't get the RepRap host to process it.

# Experimental extruder

Saturday, 3rd May 2008 by Nophead

I want to see how much of the Darwin design I can make out of HDPE as that is the plastic I have the most of and is the easiest to get hold of. It should also be the cheapest but I think I got a very bad deal with mine.

To extrude HDPE quickly, without losing accuracy, requires a fan blowing on the work piece while extruding at around 240°C. The PTFE insulator in the extruder starts to lose its strength under these conditions and it also extends about 0.5mm due to thermal expansion. The JB-Weld heater insulation also degrades rapidly. To address these problems I am working on a design using stainless steel as the insulator, which I first blogged [here](#). Here is a second lash up I made to progress the idea :-



At the bottom is a brass nozzle made by the man himself, Adrian Bowyer, and is described [here](#). It has already been superseded with the anti-ooze design shown [here](#).

Above that is a brass barrel that came from [BitsFromBytes](#), with my experimental [Cerastil](#) heater on it. I attached a thermistor to the barrel with JB-Weld.

The brass barrel is screwed into the end of a 1/4" stainless steel tube. The other end has been tapped with a 1/4" UNF thread and screwed into a small north bridge heatsink from a PC motherboard (40 x 40 x 15mm). I drilled through the centre and tapped it. To lock it in place and give a good thermal connection I made a square nut from a piece of 10mm aluminium bar. I spread heatsink compound on the threads.

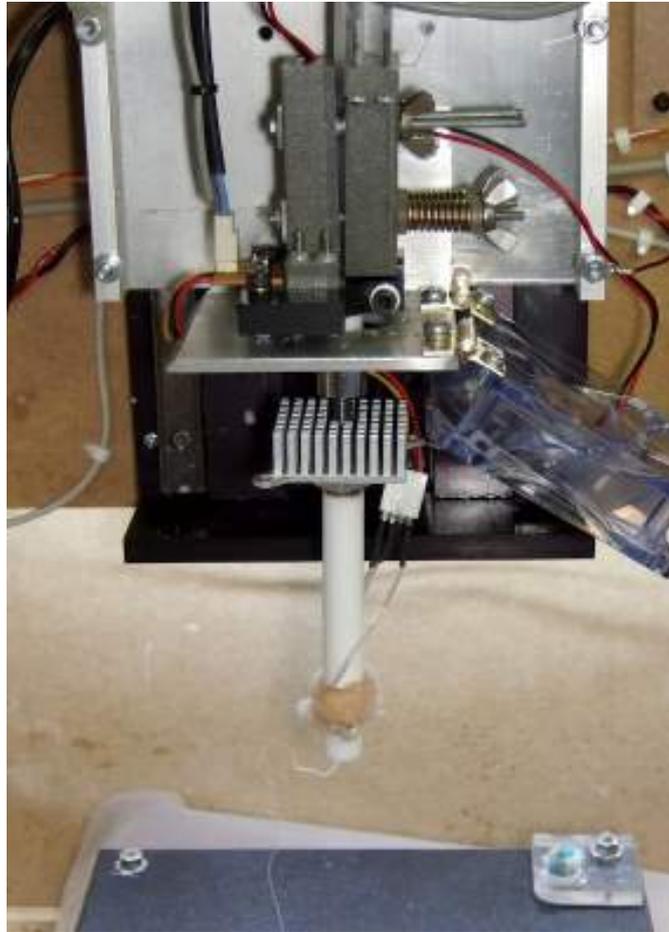
The top of the stainless steel tube is screwed into an old PTFE barrel to join it to the pump. The barrel had swollen so that it wouldn't hold an M6 thread anymore, but fortuitously it seems to have swollen just enough to match 1/4" UNF.

This is by no means the final design, it is far too long and flimsy, it's just to test the concept using existing parts.

I also wanted to try insulating the barrel and nozzle with PTFE. I made an end cap that fits over the nozzle by plunging an 8mm end mill into a 12mm PTFE rod :-



The idea of this is to keep the fan wind off the nozzle and also give it a non-stick surface so that when filament curls upwards and will not stick to it. I also insulated the stainless steel tube with a piece of 12mm PTFE rod with a 7mm hole drilled through it. Here is the completed assembly :-



The gap in the PTFE where the heater and thermistor are and where the wires emerge is covered with fiber class wool. I hate the stuff, I only have to think about it for it to make me itch all over. It is a much better insulator than PTFE though, but I wanted something smooth and slender to not disrupt the airflow from the fan too much.

The wires are sleeved with PTFE insulation and then plugged into a floppy drive connector. So everything at the hot end is good for about 300°C.

How well does it work? Well it took me a long time to be able to get it to extrude HDPE semi reliably. Thermally it works well. With the fan off and the barrel at 250°C the heatsink only gets to about 45°C, easily cool enough to mate with HDPE, ABS and probably PLA and PCL as well. With the fan blowing it cools down to room temperature. The heater power goes from about 60% to 80% so the insulation works well enough. A better idea might be to lag the pipe with a thin layer of fiberglass wool and then wrap it with PTFE baking parchment to give it a smooth outer surface. Or maybe an outer metal pipe with fiberglass in between.

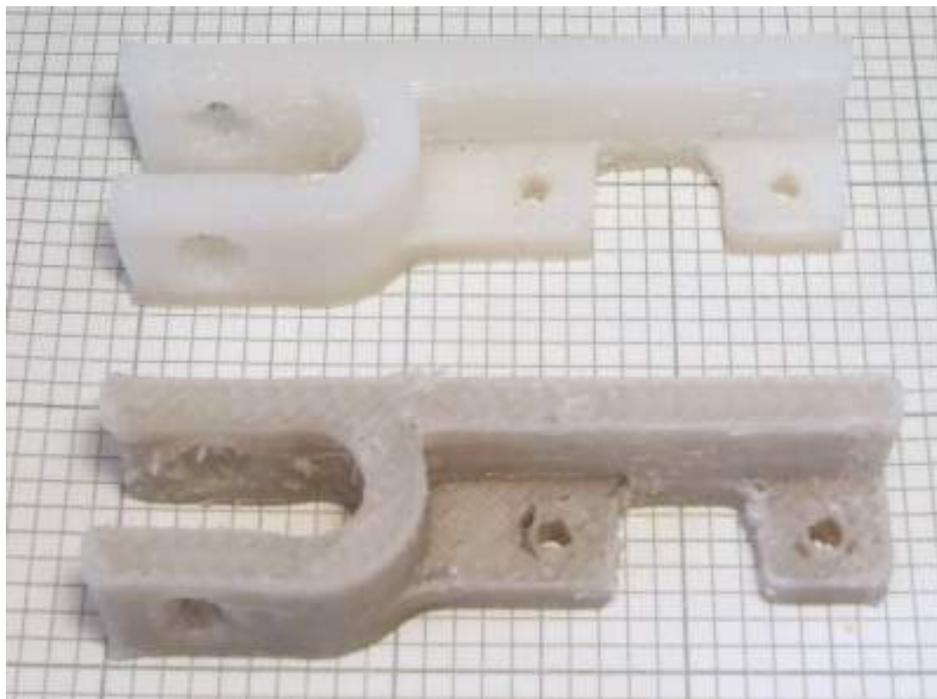
Mechanically it is not that great. It seems to need a lot of force to extrude. I had to open up the hole in the nozzle from Adrian's 0.4mm to my standard 0.5mm. I also had to up the temperature to 250°C. I think this is mainly due to where I am measuring it and how I calibrated the thermistor. Previously I measured the nozzle temperature and calibrated it with a thermocouple inserted into a hole in the nozzle. With this version the thermistor is in a notch on the surface of the heater barrel and I calibrated it with a thermocouple inside the empty barrel. Looking at the value of beta that I got I think that it is considerably hotter inside the barrel than the thermistor is outside. I am not

sure how this is. With the heater on the outside of the barrel I can't see how the inside could be hotter. Perhaps the thermal connection of the thermistor to the barrel, via JB-Weld is not as good as it could be. When sited in the acorn nut nozzle it was half buried in a hole.

Even with the nozzle removed it is quite hard to extrude 3mm filament by hand. Part of this has to do with how long the total barrel is and the fact that it has three joints. The inside of the stainless steel barrel is not as slippery as the PTFE. It might also be the case that the molten section extends further up the barrel causing more viscous friction. I plan to shorten the whole thing considerably: I will combine the clamp with the right angle bracket and take the tube right up to the base of the pump. I will support the heatsink with a cradle structure resembling an upside down table. More importantly, I will shorten the heater barrel by combining it with the nozzle and screwing the tube into it. Making it from aluminium, which is two and a half times a better conductor than brass and easier to machine, should make it easier to get a consistent temperature measurement.

As there is a continuous temperature gradient down the stainless steel, the point at which the plastic melts will be about halfway up so I think the heated nozzle can be quite short indeed. The limiting factor is how long it takes the heat to get to the centre of the filament with the very poor thermal conductivity and high specific heat capacity of the plastic.

Here is an HDPE version of the opto bracket with my best PCL version behind :-



I have no idea why it is so grey. It is not as neat as the PCL one but most of the errors are due to blobs forming when the extruder moves between extruding. These cause the nozzle to be displaced sideways when it gets close because it is so flimsy. Shortening it and supporting it properly will improve matters for sure. I also need to incorporate Adrian's anti-ooze valve somehow.

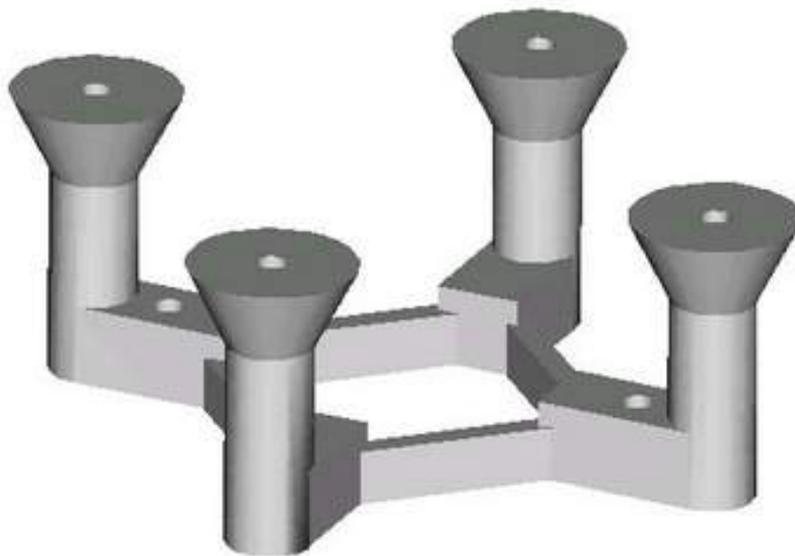
# Cat's cradle

Monday, 5th May 2008 by Nophead

I hit another milestone today: HydraRaptor made the first part that I designed myself, using the ArtOfIllusion application. It is the first time I have done any 3D modeling and it is much harder than I thought it would be.

Adrian Bowyer has written a set of hints and tips [here](#) and I needed to use every single one of them. I don't know how anybody can use ArtOfIllusion without his guide.

The reason it is difficult is that you have to build up complex 3D shapes by composing primitive shapes like blocks and cylinders with boolean operations like union, intersection and subtract. That is fine but you are not allowed to do boolean ops between objects that have coincident or tangential faces. If you do, then you create non manifold objects which cannot be converted to STL files. However, you generally do want join things with a common faces. Here is the object I designed :-

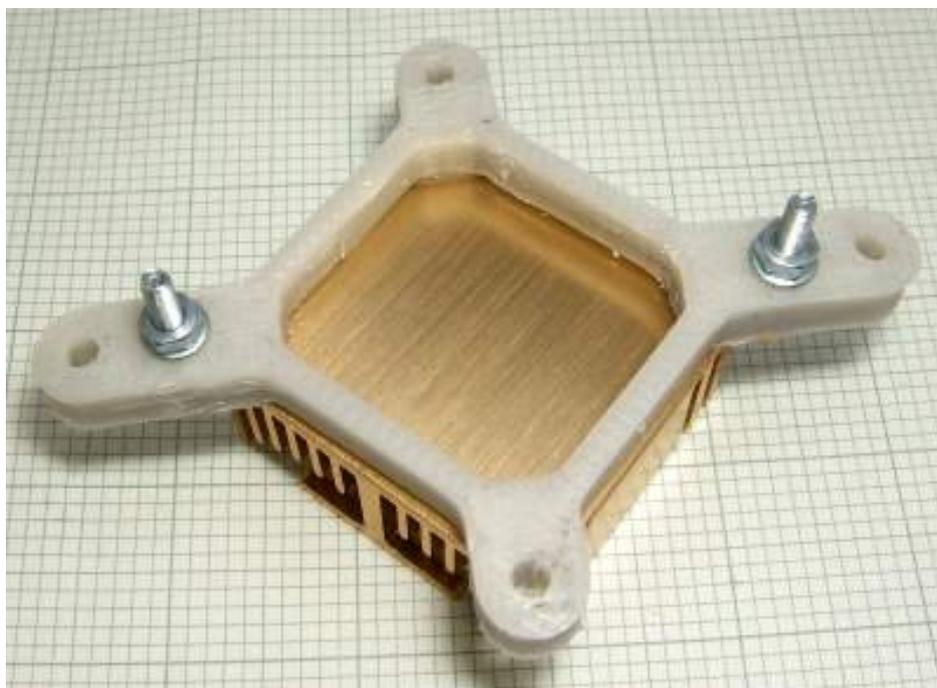


It is a cradle to support the heatsink of my high temperature extruder design. If you take one of the upright legs as an example you see it's a cylinder that meets a rectangular lug with a common face at the bottom and tangential joints at the sides. It also meets the cone on the top with a common face. All of these are not allowed: I had to make the cylinder slightly too long and slightly bigger in diameter before unioning it with the cone and the block. That left it protruding slightly at the bottom, which is solved by subtracting a large flat rectangle from the base.

Another problem is that if you have long strings of boolean operations the application becomes very slow doing anything. That is solved by converting the results of boolean operations into triangle meshes. It solves the speed issue but then for some reason boolean operations on the resulting triangle mesh only offer intersection and subtraction. To restore the possibility of union

you have to optimise the triangle mesh in the solid editor. Not hard, but not intuitive and very time consuming.

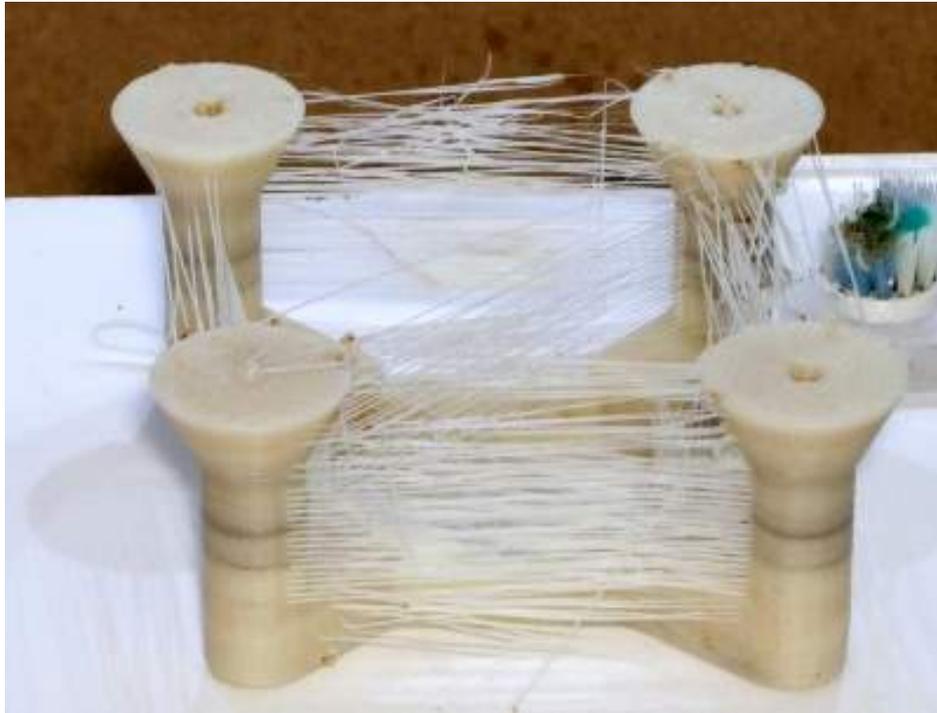
I tried to make the object in HDPE with my lash up stainless steel extruder but it was not reliable enough. This was the first attempt which stopped short due the filament slipping in the pump: -



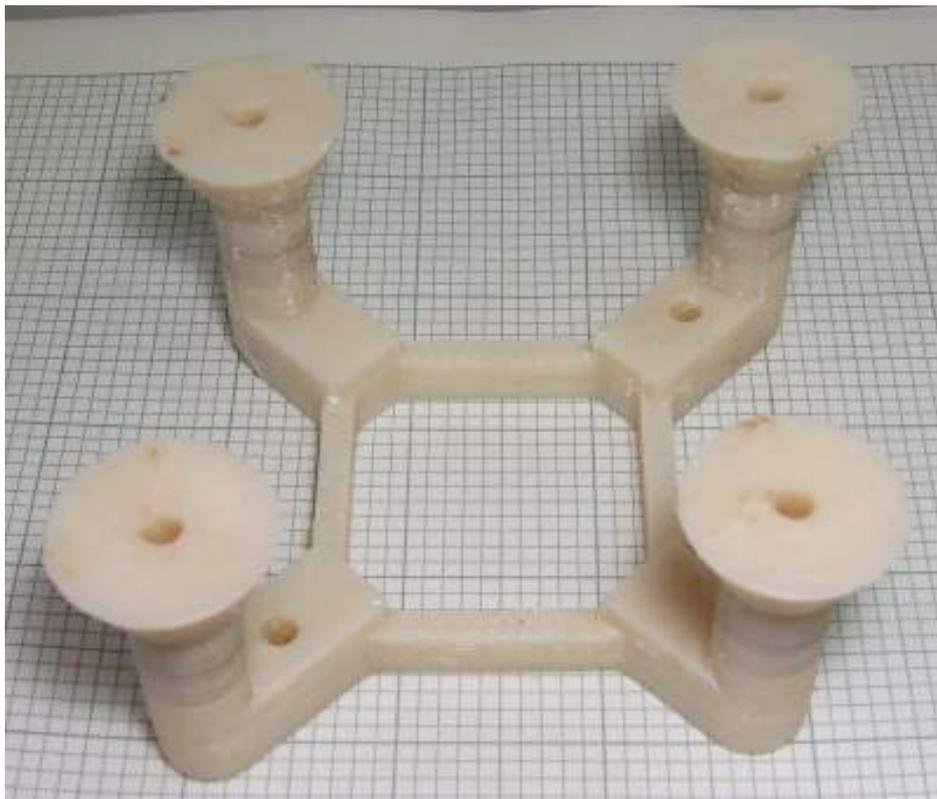
I also realised at this point that two of the columns were too close to the heatsink. Other attempts resulted in either the filament slipping, or the GM3 clutch breaking free. I had stuck it with super glue, but that does not hold very well, so in the end I welded it with my soldering iron.

It takes an enormous amount of force to extrude with the stainless steel barrel and I am beginning to think the idea may be fatally flawed. I think that because there is a slow temperature gradient down the barrel you have a point where the filament is only just molten so it is very viscous, so is hard to push past that point. With the PTFE barrel the temperature will fall away quicker and the walls are also much more slippery.

I will try again with a much shorter barrel, but to get the object made, I put my old extruder back together and made it in ABS: -



As you can see lots of stringing due to extruder overrun, but easily cleaned up with a penknife and drill. It is much easier to remove strings from ABS and HDPE objects than it is from PCL.



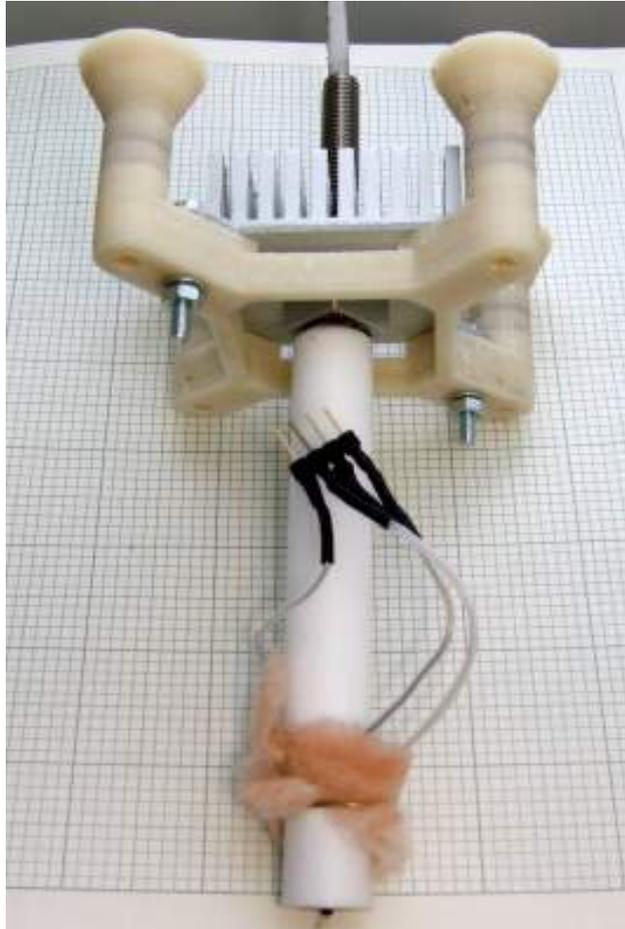
I think the dark lines on the posts are grease from the extruder bearings.

All in all I think it worked very well: this is my first ABS object, other than test blocks, and it is also the largest and most complex object I have made so far. It is a bit warped underneath because I

didn't use a raft and it is 100% filled. As it happens the underside does not matter at all for this part. It took just over 2 hours so I went for a walk and left it to it.

I designed the shape for HDPE, the objectives are for it to hold the heatsink rigidly and not restrict the airflow too much. Had I designed it for ABS I would have made it a bit less chunky.

Here it is with the heatsink installed: -

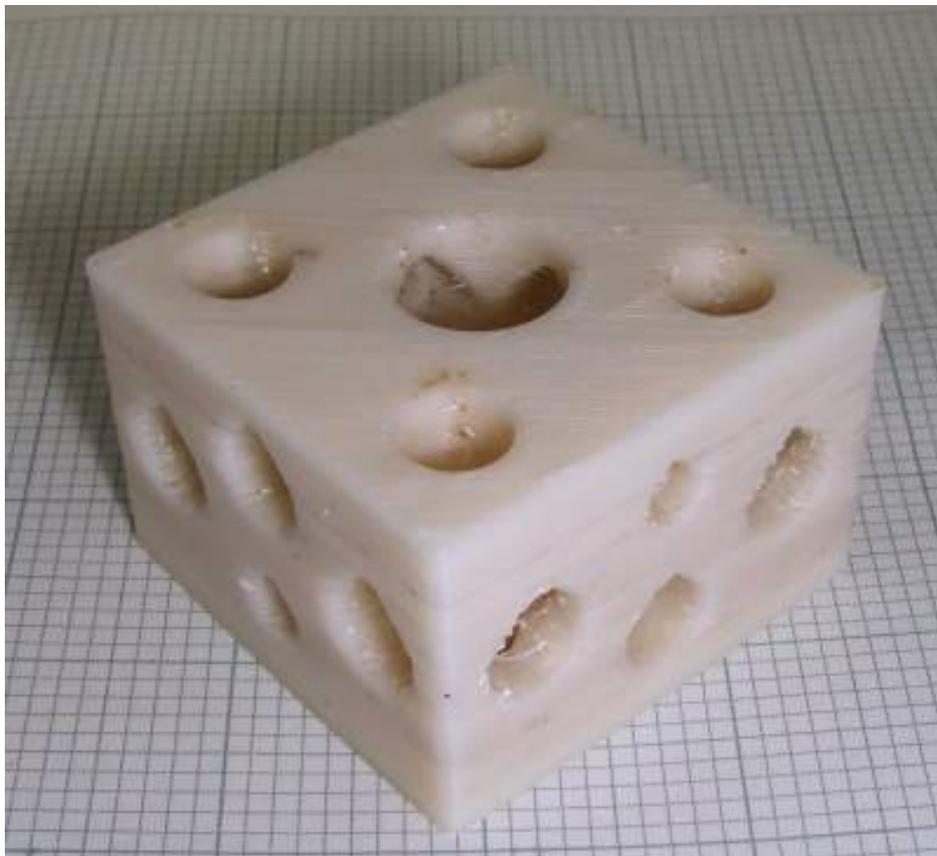


Next I need to make a new extruder support bracket / clamp to mate with this part to continue my attempt to make the high temperature extruder.

# Swiss cheese

Tuesday, 6th May 2008 by Nophead

HydraRaptor made a Darwin corner bracket in 50% filled ABS this evening: -

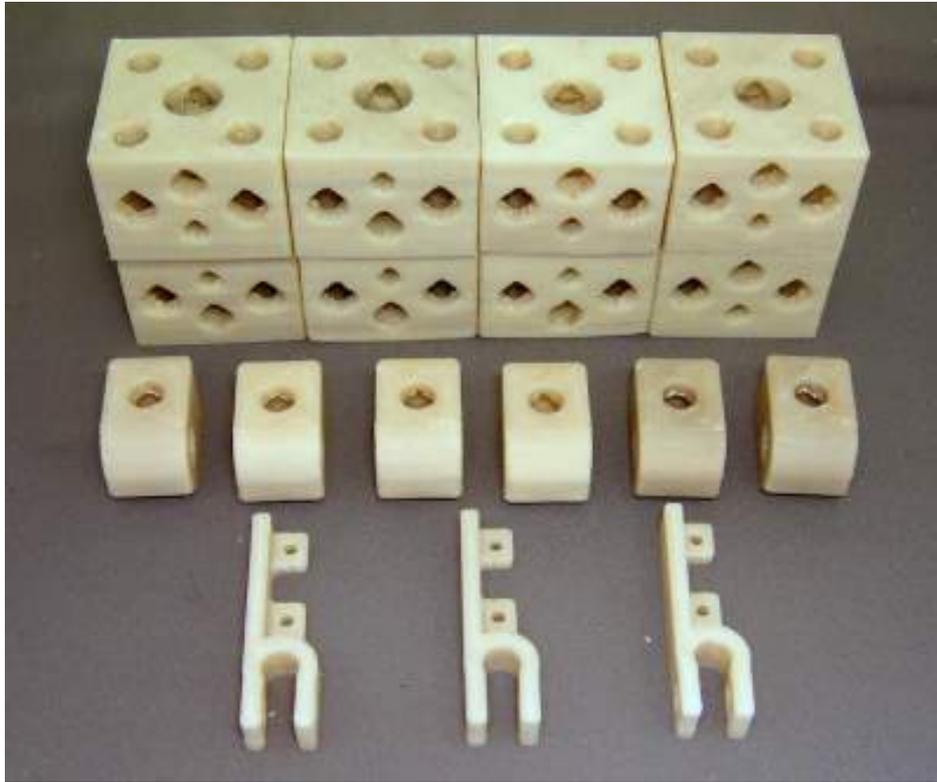


It took 2 hours 35 minutes. It feels pretty sturdy but there is some delamination through the thin section of the corner facing the camera. A bit of a weak spot in the design I think. Also the base is a bit warped as I didn't use a raft. I don't know if these matter as I haven't worked out what all the holes are for yet. I need to make seven more for a Darwin. I will probably do a 100% version for comparison.

# Stepping up production

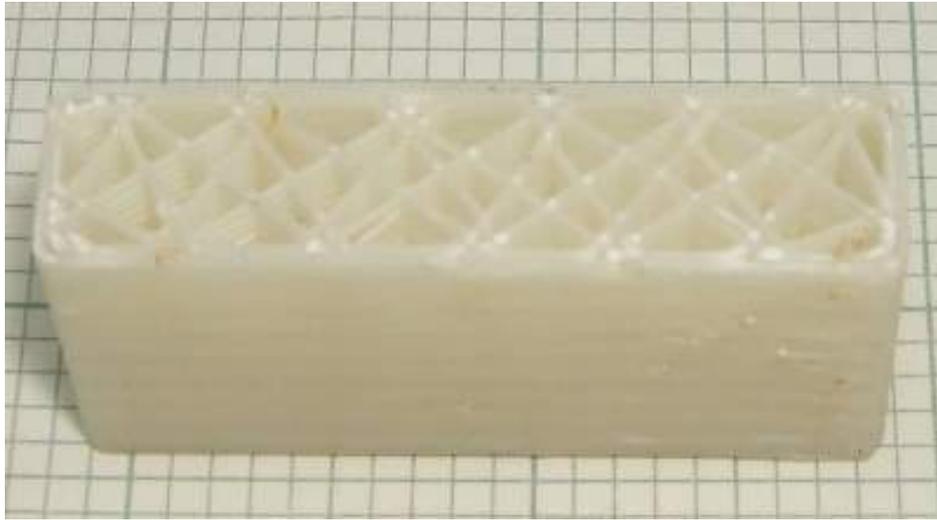
Monday, 19th May 2008 by Nophead

As HydraRaptor seems to be working so well with ABS I decided to put my high temperature extruder design on hold and go for making a set of Darwin parts in ABS. This is how far I got before my extruder wore out again: -



The flexible drive cable disintegrated and most of the JB-Weld has fallen off.

Using Enrique's Skeinforge slicer I can make very sparse objects that are still strong when made in ABS. I set the infill to 25% but I am not sure exactly how Skeinforge interprets it. The infill lines are not parallel so they get further apart the longer they are. Large voids are very sparse indeed and smaller voids look like 25% fill.



The outer wall is always two filaments thick, one is the perimeter and the other is the ends of all the infill zigzags that meet each other. With 0.5mm filament and a layer height of 0.4mm the filament threads are 0.6mm wide so the side walls are 1.2mm thick. I set the number of solid layers to 3 so the top and bottom are also 1.2mm thick. Skeinforge is clever enough to make layers with some areas 100% fill (where they are less than three layers from the top or bottom or internal surface) and other areas sparse. Very clever stuff, which really speeds up the build process but still gives remarkably rigid and strong objects.

I made four of Darwin's eight corner blocks (taking about 2.5 hours each) but I was unhappy with the amount of warping I got when not using a raft. I decided to develop peelable rafts and reusable bed material, like commercial machines have, before making any more parts. That took a lot of experiments to get right but I now have a workable system for ABS.



The bed material is the advertising board I used for ABS before, but this time I am using the back. Unfortunately I don't know what it is. It is very buoyant in water and self extinguishing if I burn it. ABS bonds to it very well. If I extrude the object directly onto it then it is impossible to remove. If I put down a sparse raft first at a low temperature I can remove the raft with a penknife. It blisters the surface but that does not seem to matter because the raft presents a smooth surface to the

object. It just gets a bit harder to remove the raft each time as the surface gets more blistered.

The board is not strong enough to resist the warping on its own so I stuck it to the back of some floor laminate with Evostick contact glue. Even that could not hold the edges down, hence the metal strip.

The first raft layer I put down is a 1mm filament zigzag with a 50% spacing, extruded at 4mm/s @ 200°C with a nozzle height of 0.7mm. Because the layer is so thick and extruded quite flat, it absorbs any surface irregularities and makes the initial head height less critical. Spacing it 50% allows it to spread sideways, if the head is too low, and also allows it to be removed. 100% fill is impossible to remove and the head height becomes critical. If it is a little too low, the filament is wider but there is nowhere for it to go, so it builds up on the nozzle and blobs.

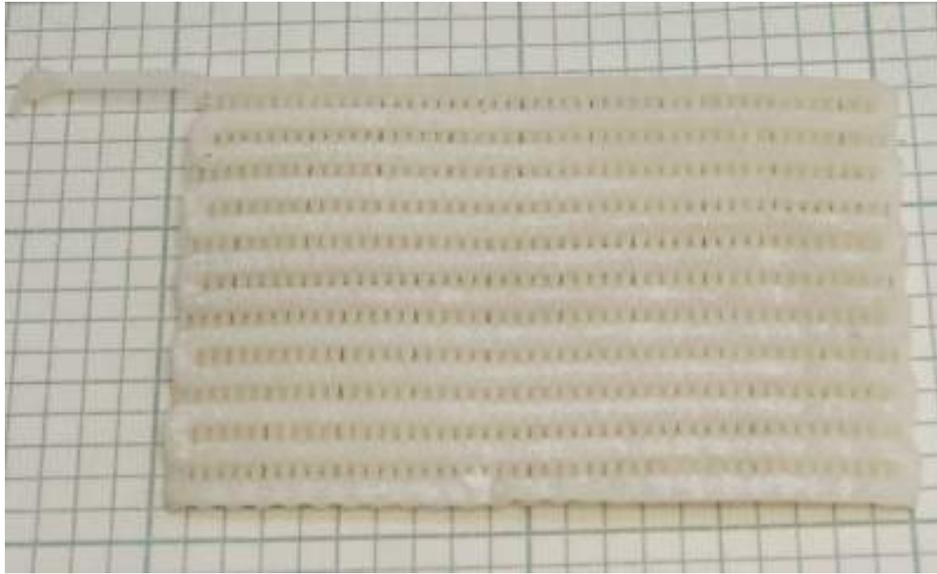
The first layer is far too coarse to build upon so I put two layers of fine zigzag the other way on top. These are 0.5mm filament extruded at 16mm/s with a layer height of 0.4mm and spaced just wide enough to not bond with itself laterally. That makes it easier to remove from the base of the object. The temperature is raised to 230°C to give a strong weld to the layers below.

Two layers are needed because the first layer has a rippled surface as it spans the wide gaps in the layer below. I put them down on top of each other rather than alternating the direction of the zigzag. That makes them weaker laterally therefore easier to remove from the object with a penknife.

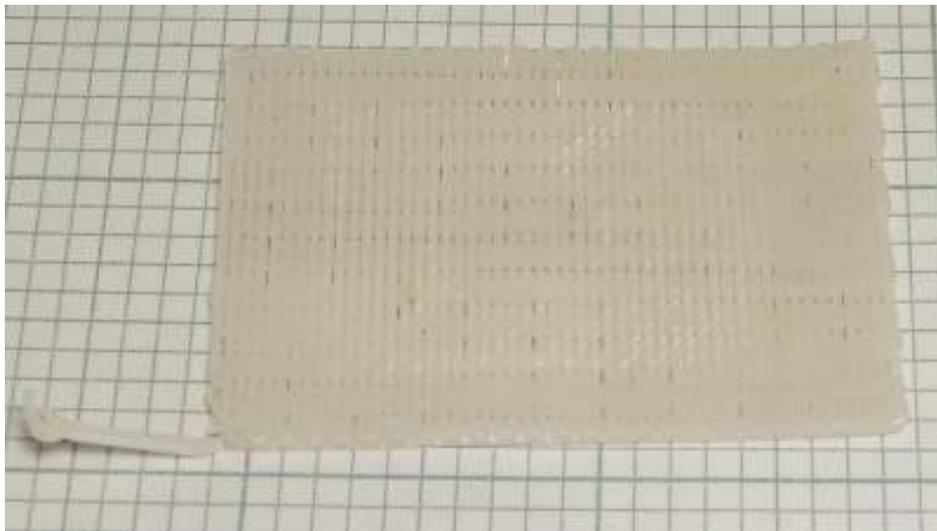
The raft uses horizontal and vertical zigzags so there is no correspondence with the object infill which is at 45°. Again that makes it easier to separate without risk of pulling a thread out of the bottom of the object.

To ensure the raft does not bond too well to the object it is cooled for a minute with the fan. The first layer of the object is then extruded at 8mm/s @ 215°C and subsequent layers at 16mm/s @ 230°C. The temperatures are critical, so depending on thermistor site and calibration, they will vary a bit from machine to machine.

This is what the bottom of the raft looks like: -

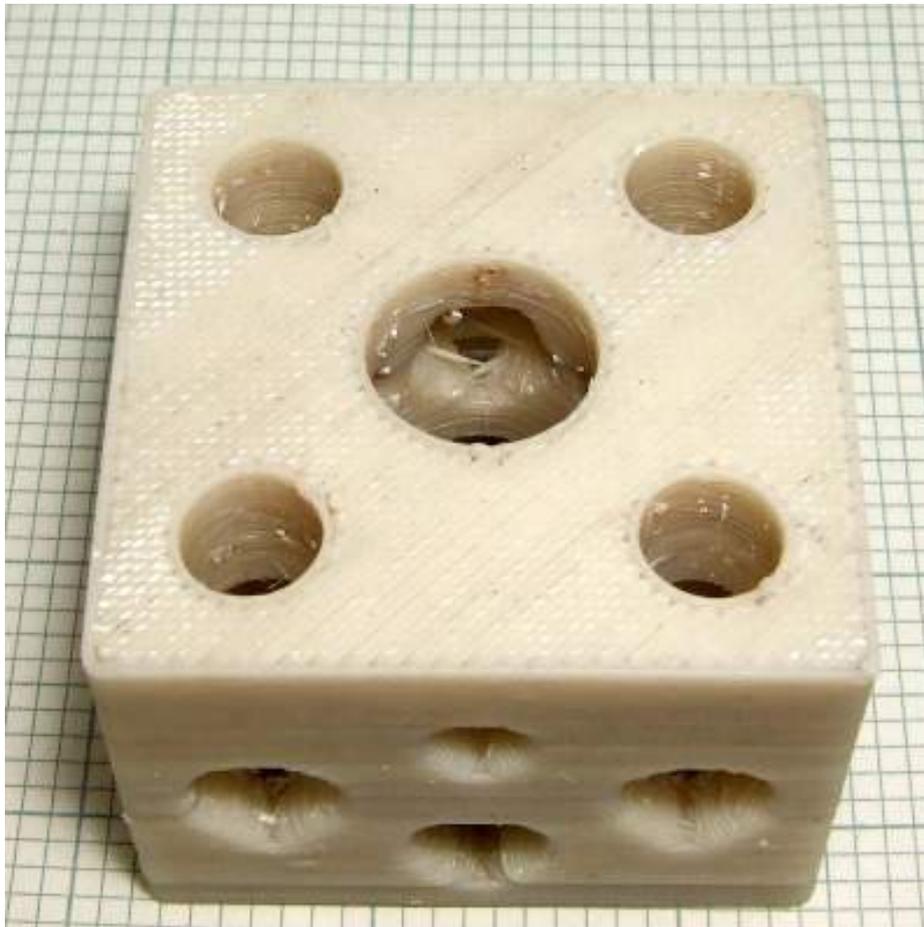


And this is the top: -



It does slow the build and waste plastic but it reduces warping and makes the bed reusable over and over again. I expect it won't last forever but you can certainly use it many times.

The base of the object is also pretty neat and tidy: -



Here are the stats for the objects I have processed so far: -

	Seconds	Filament @ 16 mm/s	Moves @ 32 mm/s	Build time	Plastic volume	Quantity required	Total build time	Total plastic
Corner bracket @ 25%	8866	122009 mm	34926 mm	02:27:46	24.0 cc	8	19:42:08	191.7 cc
Opto bracket @ 50%	1200	15902 mm	4661 mm	00:20:00	3.1 cc	3	01:00:00	9.4 cc
Diagonal tie bracket @ 25%	2178	31236 mm	3716 mm	00:34:28	6.1 cc	20	11:29:28	122.7 cc

I will update this table as I progress to make the Darwin parts.

# Mystery material

Tuesday, 20th May 2008 by Nophead

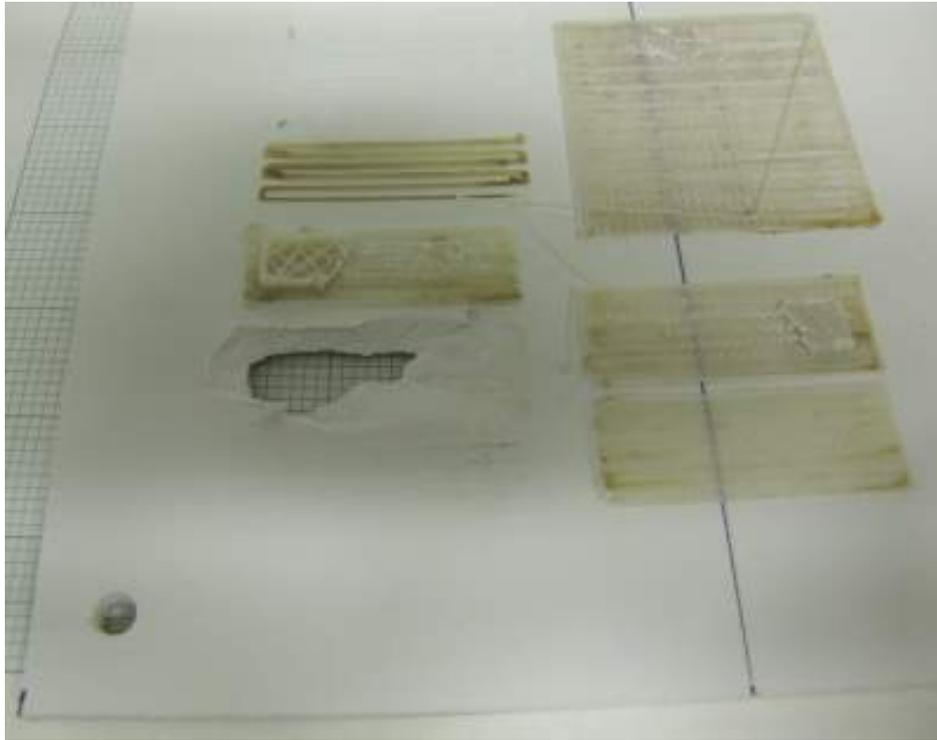
The bed material I am using for ABS works very well but the problem is I don't know what it is. My wife bought it for 10p when I was trying lots of things for HDPE and was disappointed when it did not work. She is now delighted I found a use for it as she loves to get a bargain.

It originally looked like this :-



It is about 3mm thick. Most of that is the plastic backing. On the front is printed paper, stuck on with a double sided sticky film and covered with single sided sticky film. This can be peeled off to just leave the back material so both sides of that can be used.

Here is a bit I destroyed developing rafts: -



It will bend a little but then it snaps, as you can see, when I pulled a raft off that was stuck too well.

I normally use [this](#) flowchart to identify plastic but it fails with this material because I think it is a polymer with a fibrous filler, possibly paper.

- It melts with a low temp soldering iron so is not a thermoset.
- It floats very well but it is not PE or PP, so that is probably due to a filler.
- It does not burn well and is self extinguishing.
- It gives black smoke and if anything has a yellow flame.
- It does not drip.
- The smoke has some odour but I don't recognise it. I don't know what phenol smells like though.

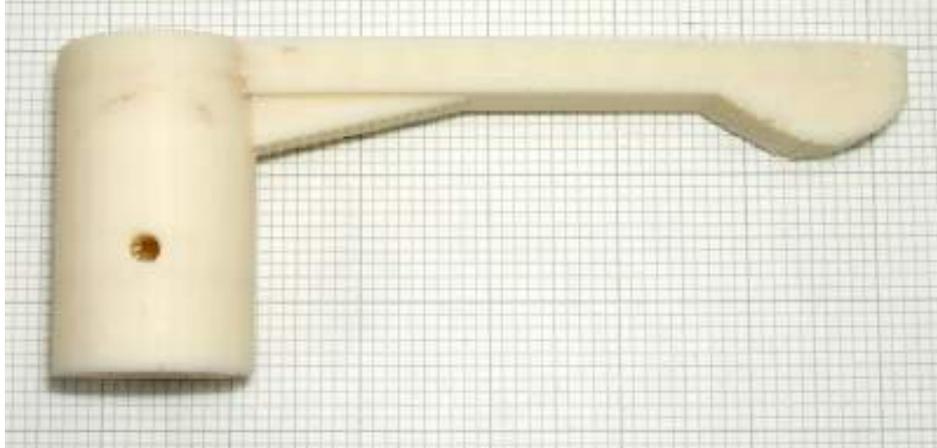
So perhaps it is PPO and a fiber. If anybody knows where I can buy it from I will be very grateful.

It is quite reusable but I expect it will need replacing sometime and other people want to use it.

# Catalogue of disasters

Sunday, 1st June 2008 by Nophead

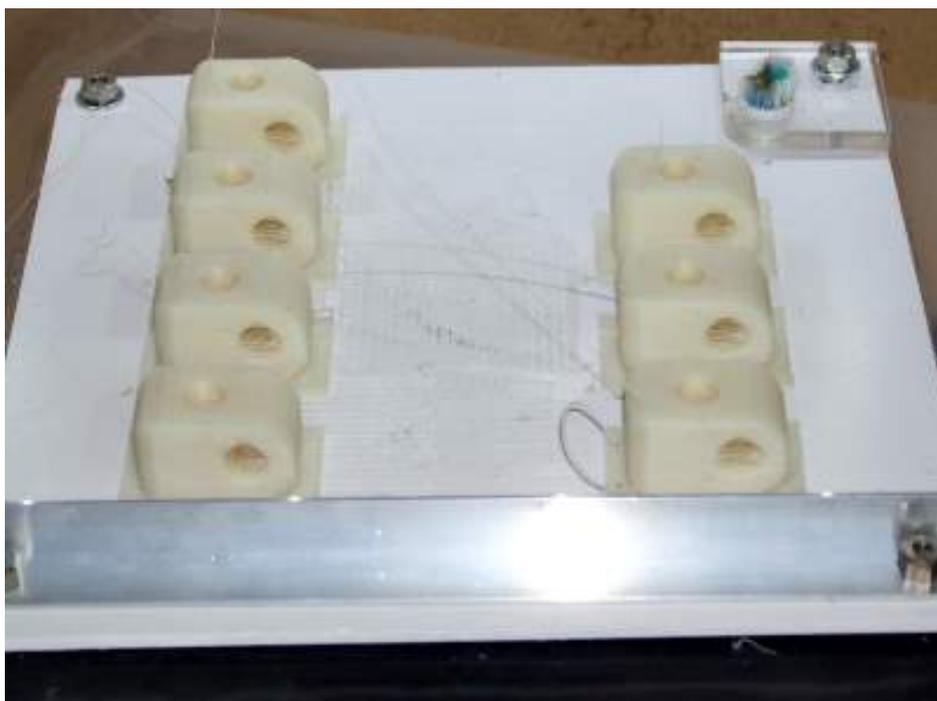
Last week things were going well. I made this door handle to be exhibited at the Cheltenham Science Festival: -



More details [here](#).

I wrote a script that can print n copies of the same object by spacing them out so that the head can get between them. It would be more efficient to print them closer together, one layer of each at a time, but if anything goes wrong then they are all scrap so I am taking the conservative approach at the moment.

With the script I managed three printing shifts in a day. I set off a batch of seven diagonal tie brackets in the morning and they were waiting for me when I got home from work.



I then printed the X-carriage during the evening and another seven diagonal tie brackets during the night.



My wife thinks it looks like a ruined church and I have to agree.

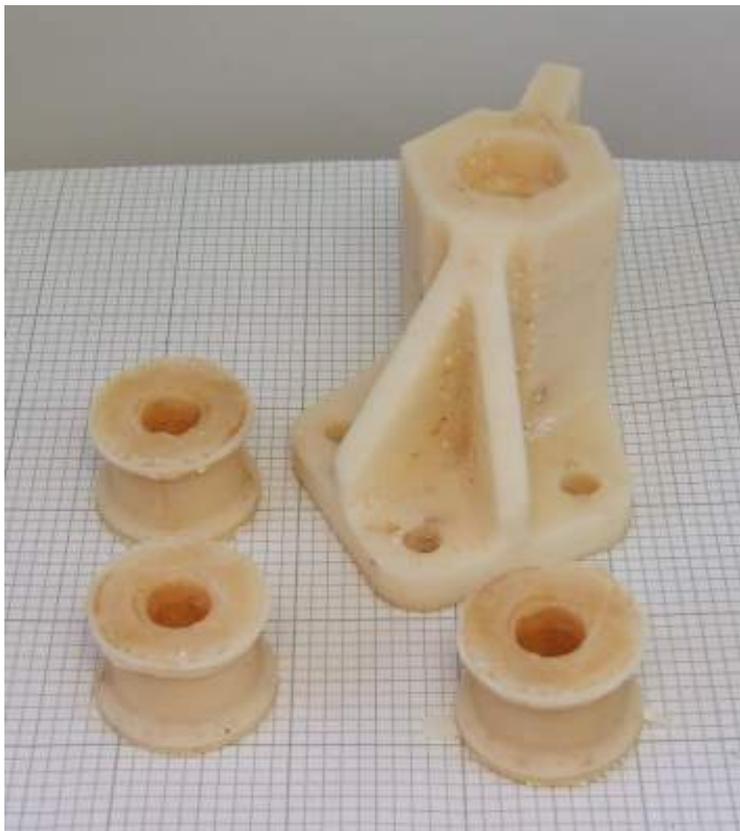
After that things started to go downhill. The flexible drive coupling broke for the third time, but that was easy to replace by soldering in another piece of cable.



The first thing I made when it was back up and running was an old version of the extruder motor bracket which allows a direct drive. At this point the JB-Weld heater insulation started to fall off leaving the heater wire bare. It seemed to miraculously stay in place and still give heat even when most of the JB-Weld had gone.

I did notice the heater duty cycle was going up, eventually reaching 100%, but that was to be expected as there was less thermal conduction from the wire to the barrel. Then the temperature didn't quite make the set point, but it was close so I carried on using the machine. I made three pulleys but they seemed to get too hot. The top was distorted and they were impossible to

separate from the raft. I put this down to them being smaller than anything I had made so far and decided to make something bigger. I left the machine making a bed corner bracket and went out for a walk. When I can back the house stank of burning plastic and the bed corner bracket was impossible to separate from its raft, and the raft was welded onto the bed material.



I finally twigged, the reason the temperature was reading low, and hence the heater was full on, was because the JB-Weld holding the thermistor had also decomposed. I don't know what the temperature was but it was way too high.

So I switched to my Cerastil heater and the nozzle from my high temperature extruder experiment. I also had to replace the bed material as it had a big hole in it where I broke off the corner bracket.

I powered it up and calibrated it and it seemed fine. I left it running for a while and it started making popping sounds and producing little clouds of smoke. Very odd, while I was puzzling over it the temperature reading started falling with the heater on. Then clouds of smoke started streaming out of the extruder.

Aha I thought, the thermistor must have come off again, but when I stripped it down I found it hadn't. What actually happened was molten ABS had escaped from the thread of the nozzle and got onto the thermistor. For some reason that must have cooled it, causing it to read low, so the heater overheated again.

I fixed the leak by sealing the thread with PTFE plumbing tape. I set the machine off again but it only got half way through a raft when the heater barrel escaped from the PTFE insulator and the

nozzle buried itself into the brand new bed material.

I made a new PTFE barrel (as the old one had obviously been softened by its high temperature excursions) but when I was reassembling it, the thermistor, which was only stuck with JB-Weld, fell off. So back to square one!

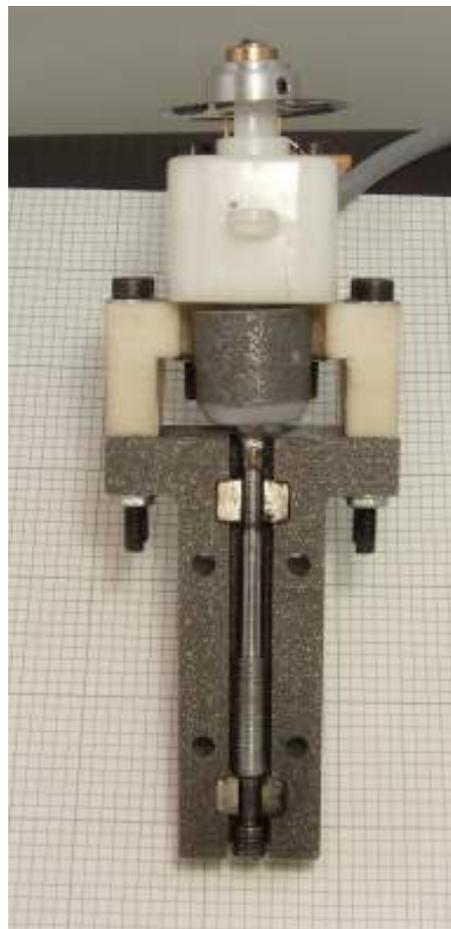
I stuck the thermistor back on with Cerastil but when I screwed the nozzle on it was too close, so it broke off again. Starting to get a bit frustrated now, to put it mildly!

I stuck the thermistor on again with Cerastil, this time after I screwed the nozzle on, but while reassembling the extruder for the nth time one of the heater wires broke off. I was able to dig out the connection and solder to it with high temperature solder.

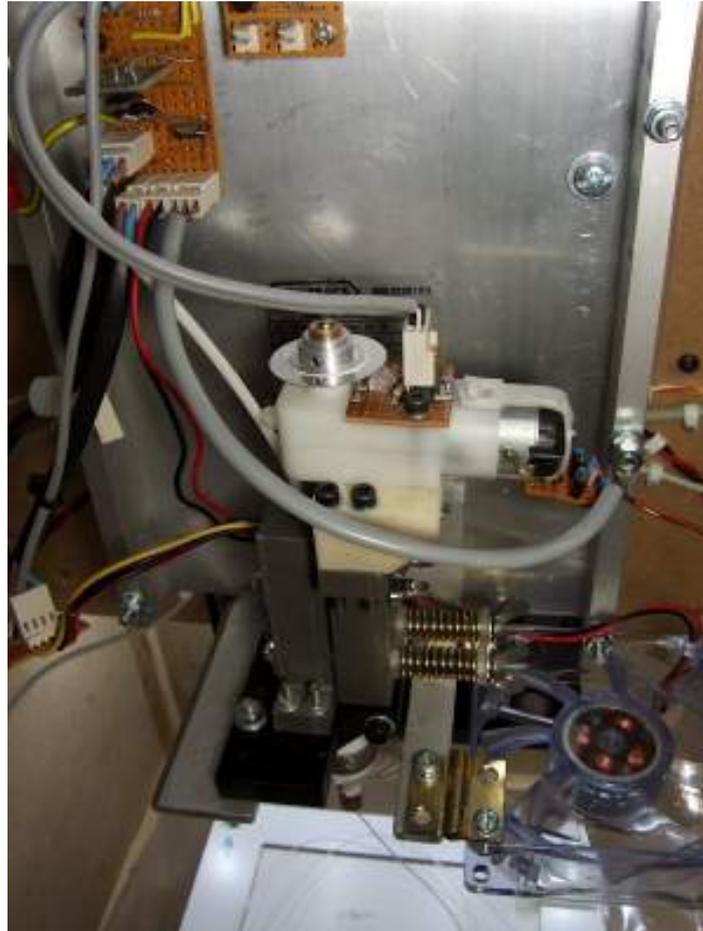
I reassembled the extruder yet again and set the machine going. Half way through the raft the drive shaft broke, not the flexible bit, but the solid bit it was soldered into!

At this point I started to think I was never going to get a working extruder again. A week had passed, I had been working on it every evening but every time I fixed something, something else broke. I had taken it apart and reassembled it so many times that the threads on the M3 studding that tensions the springs had worn away and had to be replaced.

Rather than make a new drive shaft I decided to go for the direct drive design that is slightly shorter. I soldered a nut to the end of the broken shaft and modified the coupling in the lathe to shorten it and give it a taper to clear the filament.

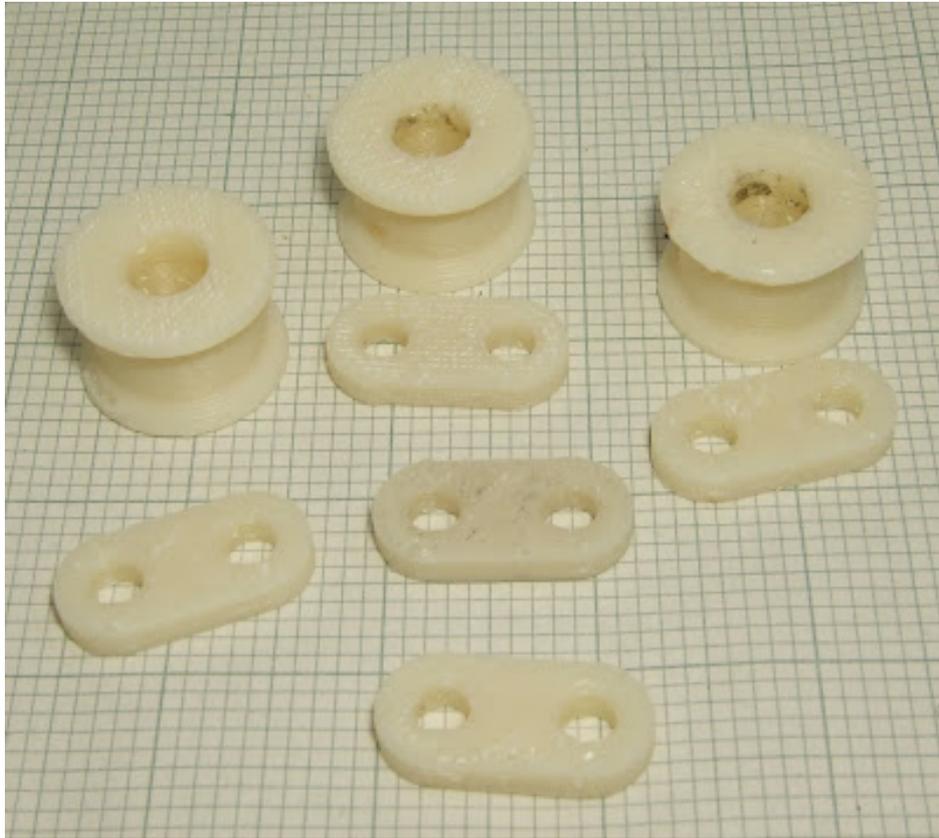


So HydraRaptor gets its first RP part.



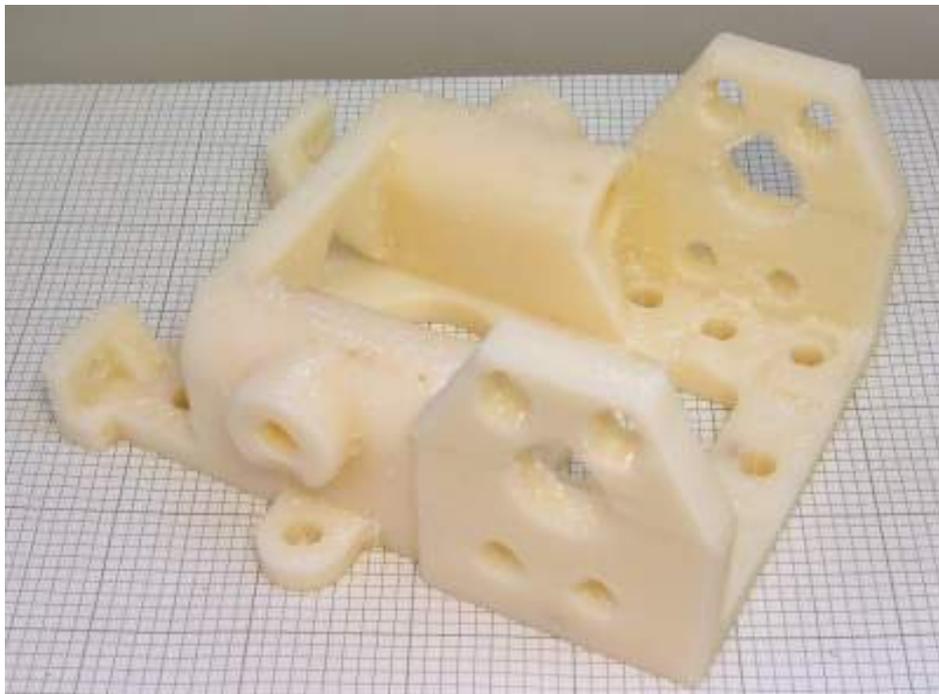
I now seem to be back up and running and have managed to knock out several more Darwin parts.

Pulleys and belt clamps: -



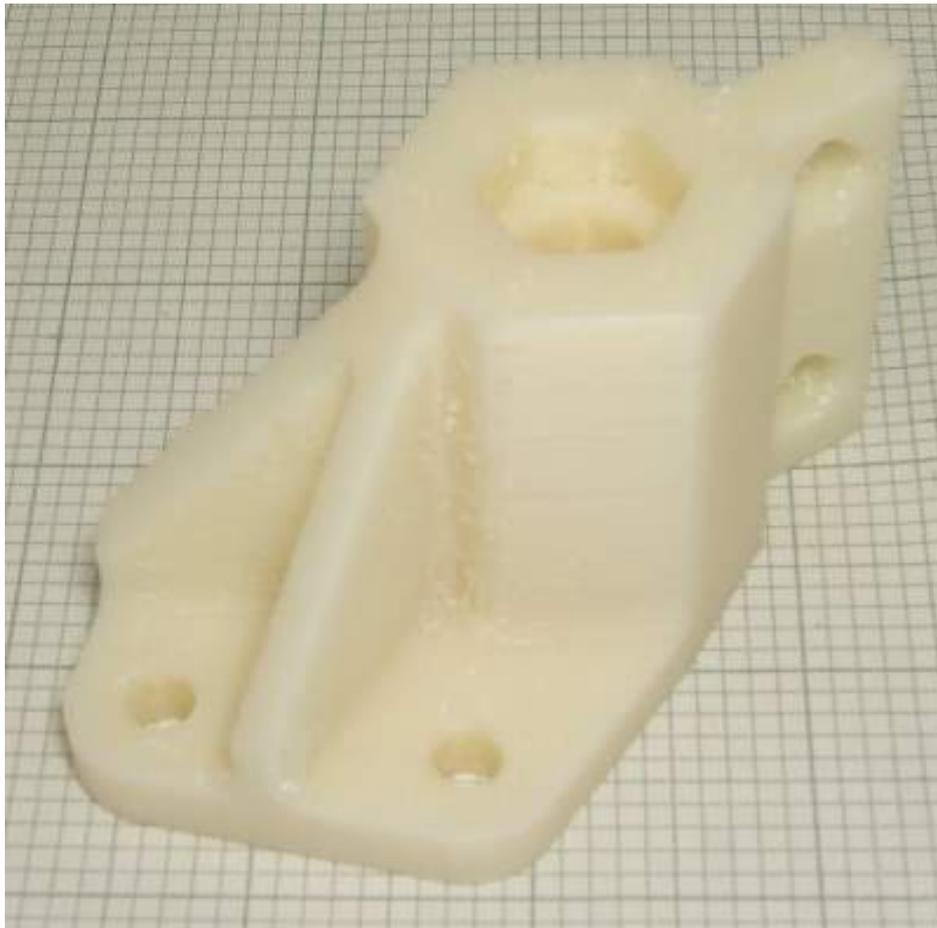
The belt clamps are the smallest things I have made, they only take about 4 minutes each.

This is the largest thing I have made, I think it is the biggest Darwin part, the X-motor bracket: -

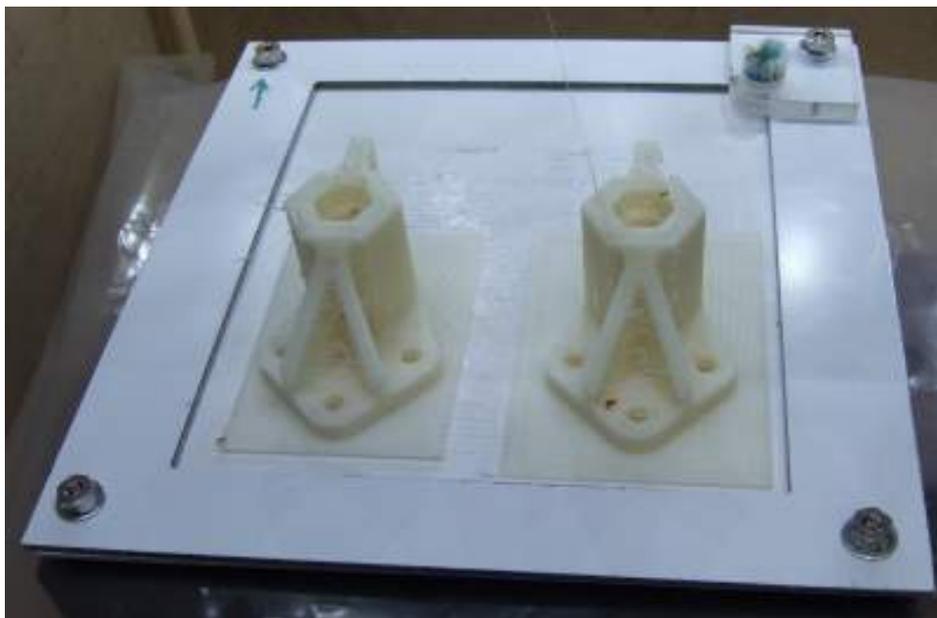


It takes about 4 hours and uses 37cc of plastic when done with 25% fill. That is just less than \$1 worth of ABS at the RRRF price of \$20/Kg.

I also made four bed corner brackets: -



I can only fit two at a time on the table: -

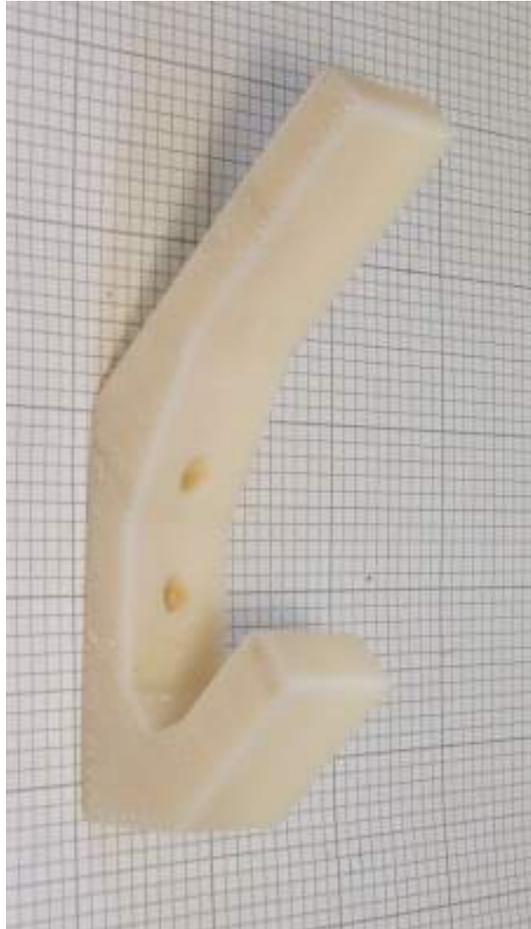


I found that the mystery bed material I am using has a glass transition below 100C so I think it is PVC plus a filler. I stick it down with double sided tape but larger objects manage to lift it at the edges so I made a frame to hold it down. It is a sheet of 3mm HDPE laminated with aluminium. I

milled the aperture in it using HydraRaptor's milling head. The only problem is it restricts the build area slightly because the biggest milling bit I have is smaller than the nozzle.

So it seems the machine is running reliably again and two of the things that persistently fail, flexible drive cable and J-B Weld have been eliminated.

I also made this coat hook for Adrian Bowyer: -



It is Adrian's design, sliced by Enrique's software, extruded through a nozzle made by Adrian. It took about 40 minutes and used about 8g of ABS costing \$0.16.

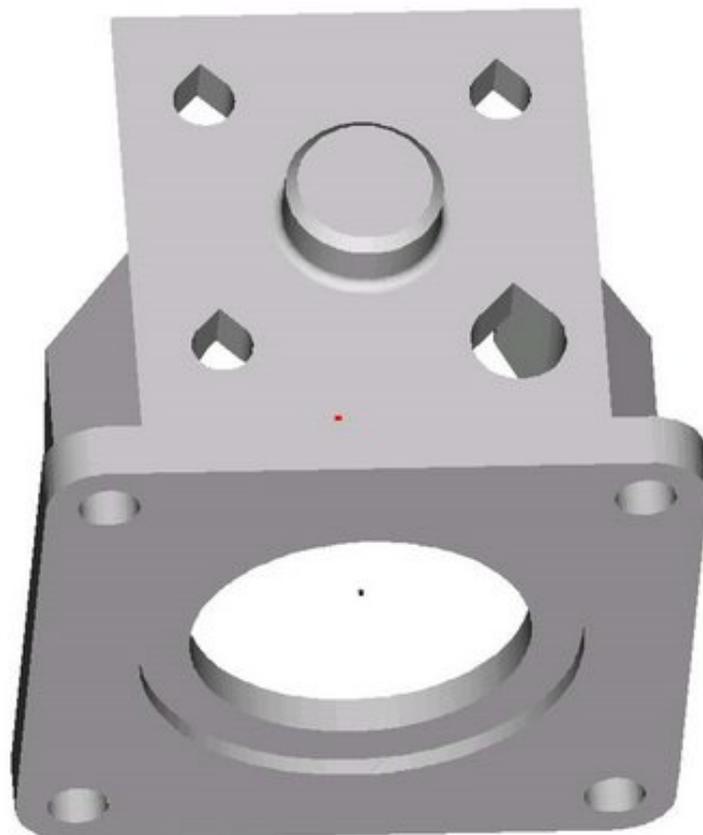
# Support, who needs it?

Friday, 13th June 2008 by Nophead

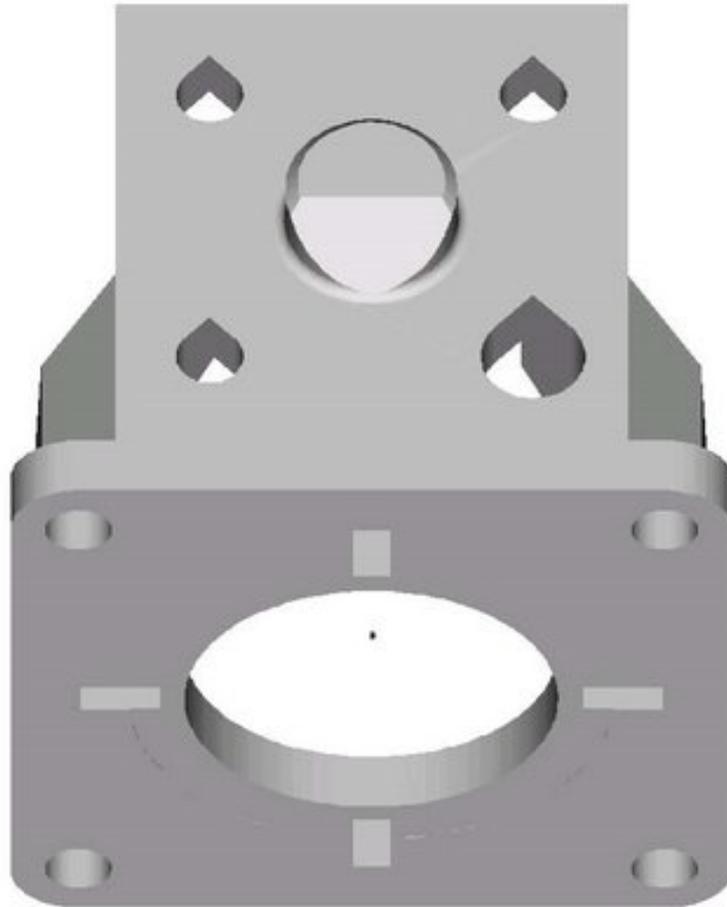
I think the original Darwin design assumed it would have a support material extruder, so some of its parts require support material to be made. I.e. they have overhangs that are more than  $45^\circ$ . Vik Olliver and Steve DeGroof subsequently modified the parts requiring support material so that they can be made without it. That allowed Vik to replicate his Darwin without a support extruder. STL files for the modified parts can be found [here](#).

At the time I was making the Y-motor-bracket for my Darwin, the modified file was missing, so I decided to see what would happen if I tried to make the unmodified version. I expected the result to be a mess.

Here is the original file, it has a recess in the bottom to fit the shape of the motor and stud coming out of the side at right angles: -

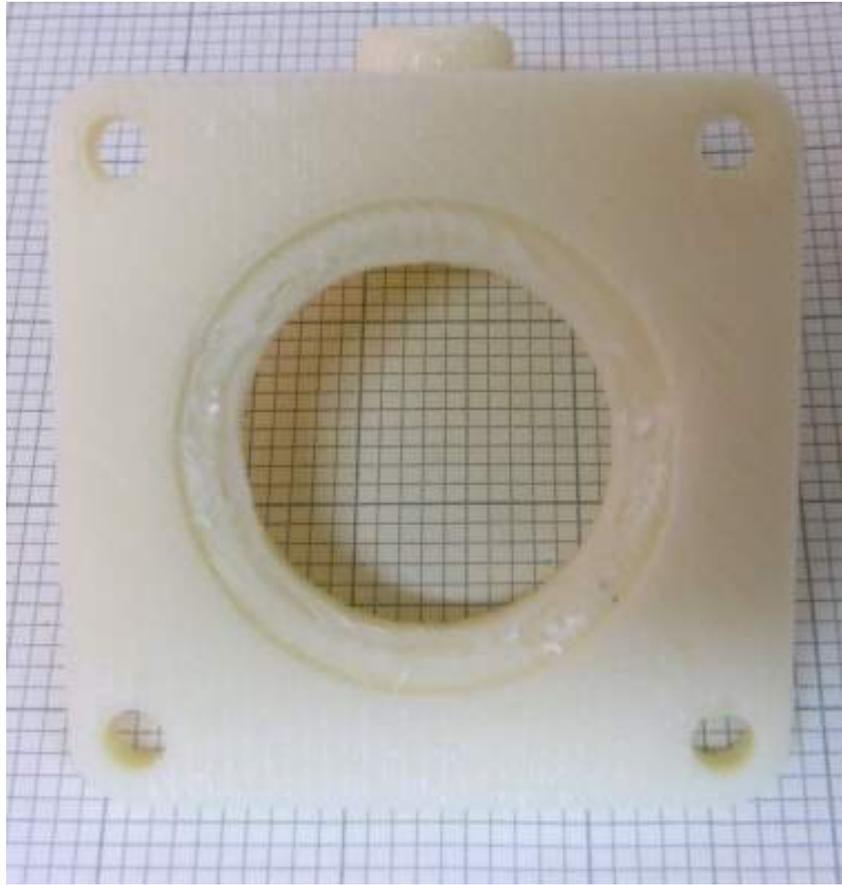


Here is the modified version to reduce overhangs to  $45^\circ$ : -



The problem with this is that it doesn't fit the motor properly. I think Vik was using a different motor.

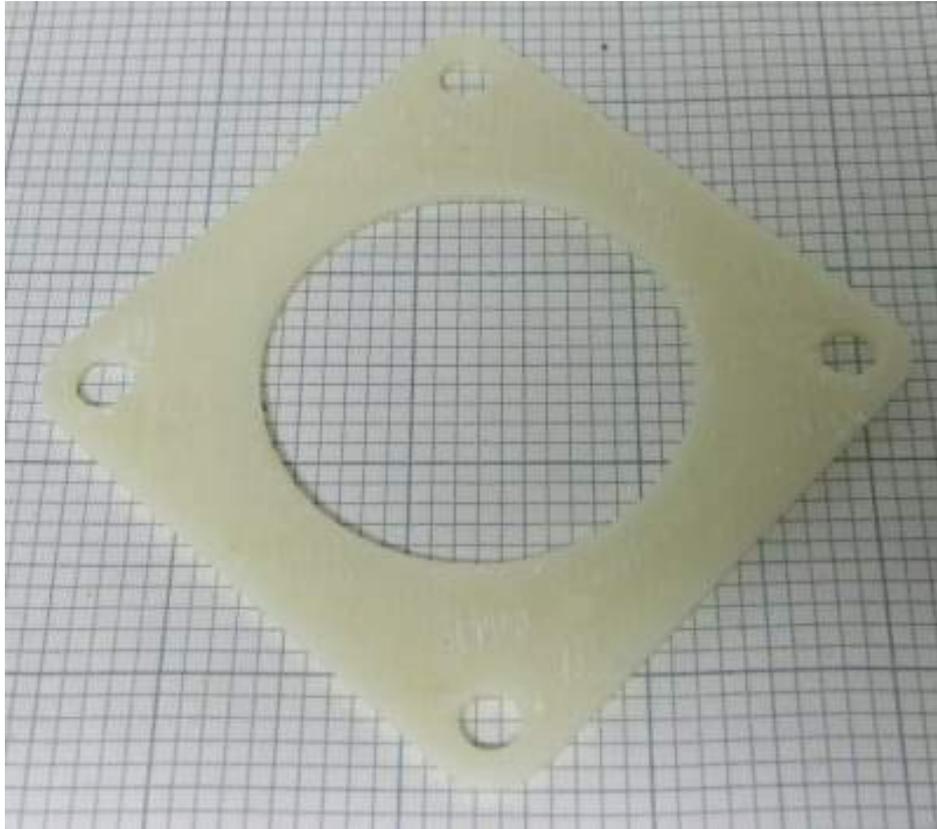
To my surprise the original version came out fully functional. It is a bit messy, some of the outline was extruded into mid air and had to be cut off, but the infill managed to build out and recover the correct shape after a couple of layers.



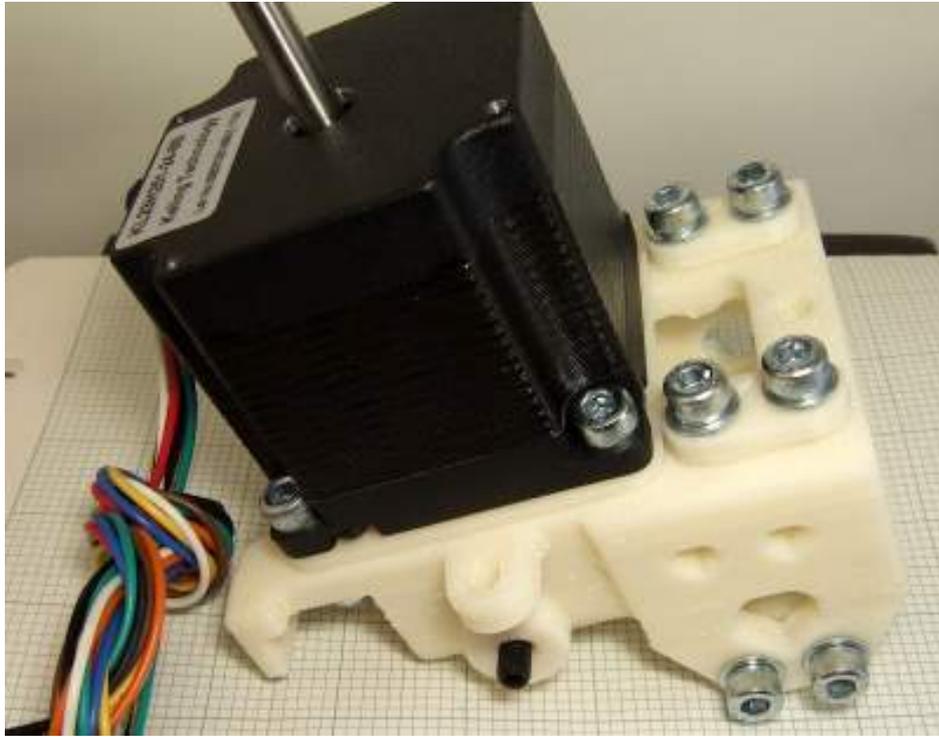
It makes me think we might be able to build out into fresh air simply by going slowly and with a fan

to cool the filament.

I built the modified version of the X-motor-bracket, but that has no recess as well so the motor did not fit it. To fix that I made a washer to replace the recess. This was simply a slice off the Y-motor-bracket: -



It is 1.6mm thick, which is four layers with my preferred settings. It seems to do the job. I had to use 20mm bolts rather than 15mm to mount the motor. The pulley is normally mounted 2mm from the end of the shaft so moving to 0.4mm from the end should compensate for the washer.

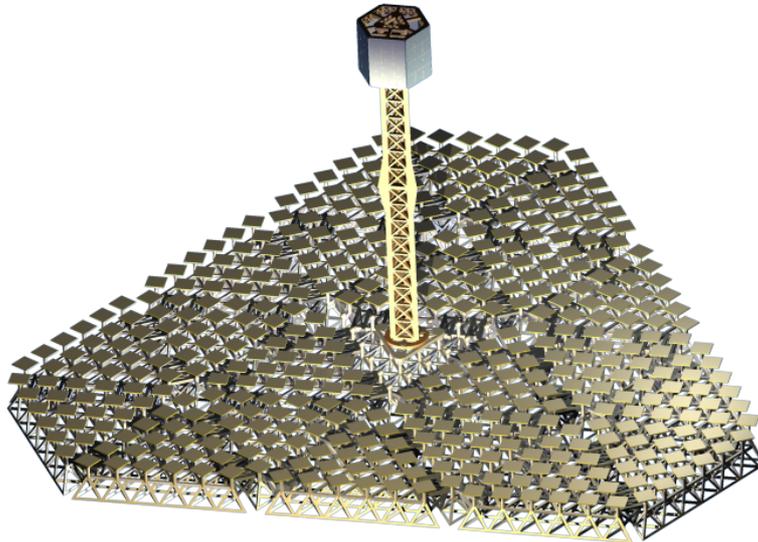


It should also be possible to use this washer on the other motor brackets. I uploaded it to the [wiki page](#).

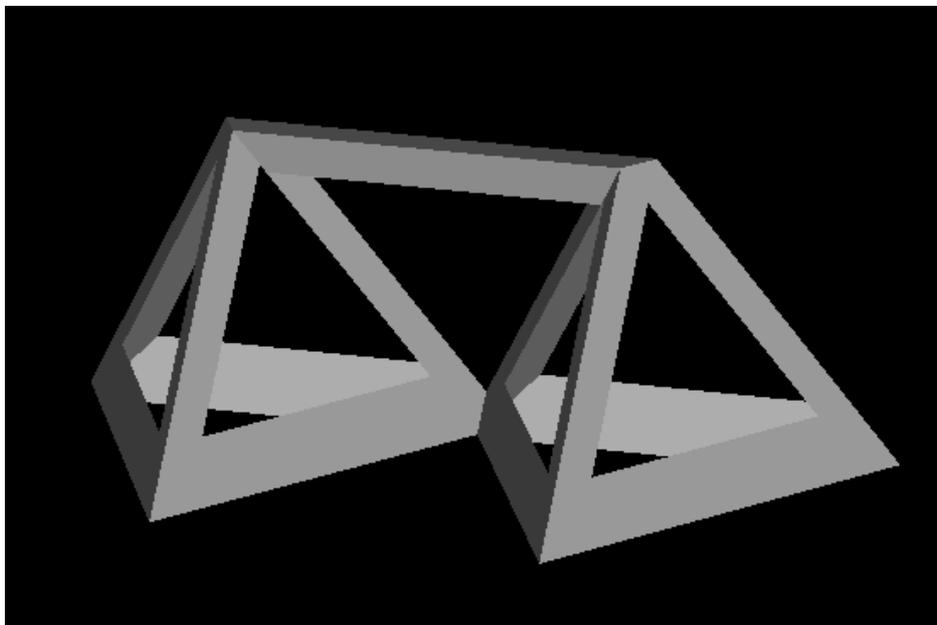
# Unsupported!

Saturday, 14th June 2008 by Nophead

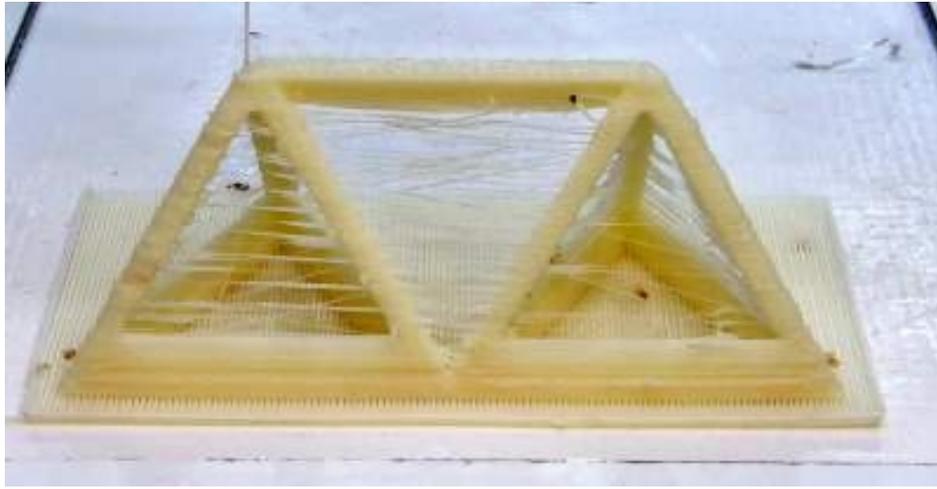
Kyle Corbitt has designed a RepRapable solar collector described [here](#).



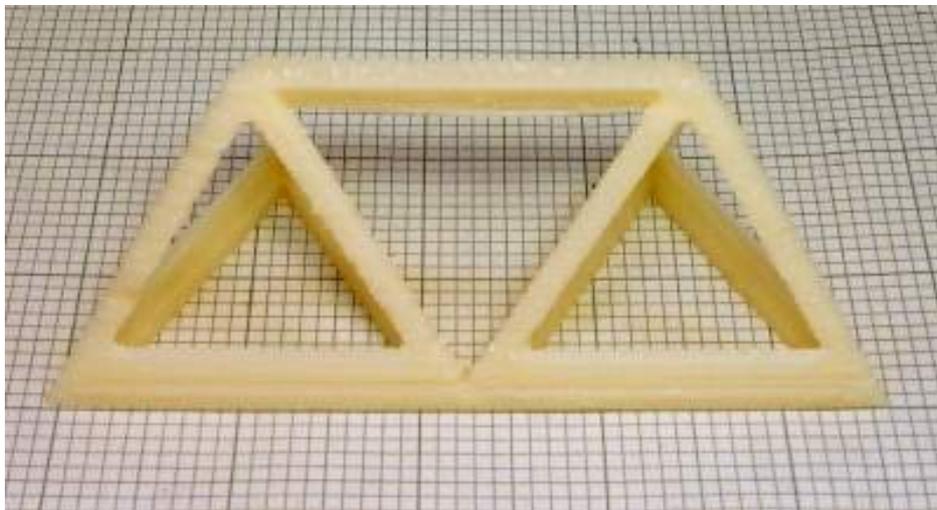
The structure is made up from a triangular lattice like this :-



The risers only overhang 30°C, so they are no problem but the horizontal beam looks like it should need support material. Kyle asked me to try building it without, so I gave it a go. Here is what it looked like after it was made: -



Very hairy but basically sound. This is it after being cleaned up with a scalpel: -



It took about 45 minutes to make and used only 7g of ABS, not including the raft. Head travel while not extruding was about 42% of the filament length but as I move twice as fast as I extrude that was only 21% of the time.

Despite the risers only being about 3.7mm thick it is very strong and rigid. I loaded the centre of the beam to 1.5Kg and it showed no sign of breaking. I also loaded one end to 6Kg with no sign of movement, so the beam could easily support 10Kg and possibly a lot more.

At the top of the base beams the triangular section goes down to zero width. The top four layers are only one filament wide so are very fragile. I don't think they add much to the strength so it would be better to truncate the top of the triangle. Interesting though because it is the first time I tried to make something this thin (0.6mm) in ABS.

Enrique added an option to make the infill go along the length of bridges but it is not actually needed for this shape. The top beam has an inverted triangular section so the first layer of it is just two parallel outlines which span the gap. The rest of the beam builds out from this at 30° so it does not matter which way the infill goes. The first few layers did sag a bit but the top of the beam is flat. An inter layer pause may have reduced the sagging.

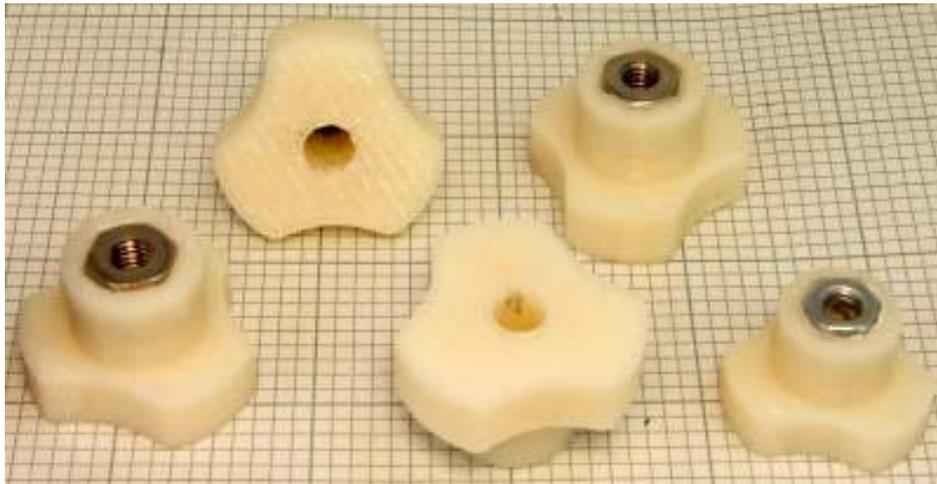
So this looks like a good way to make large structures that are light and quick to build, but still strong.

# Knobs

Thursday, 19th June 2008 by Nophead

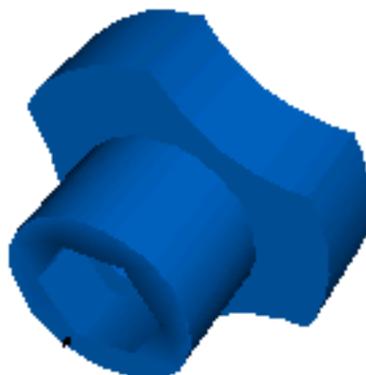
I wanted some wingnuts to let me quickly clamp the bed material to the table and release it again. The XY table came from the US so it has 2BA, rather than metric threads, in it. That means I can't get them locally and would have to order them. The cost would be about \$6 for 10 including postage, but I only wanted 4.

Then I remembered I have a machine than can make things so I made some knobs with captive nuts: -



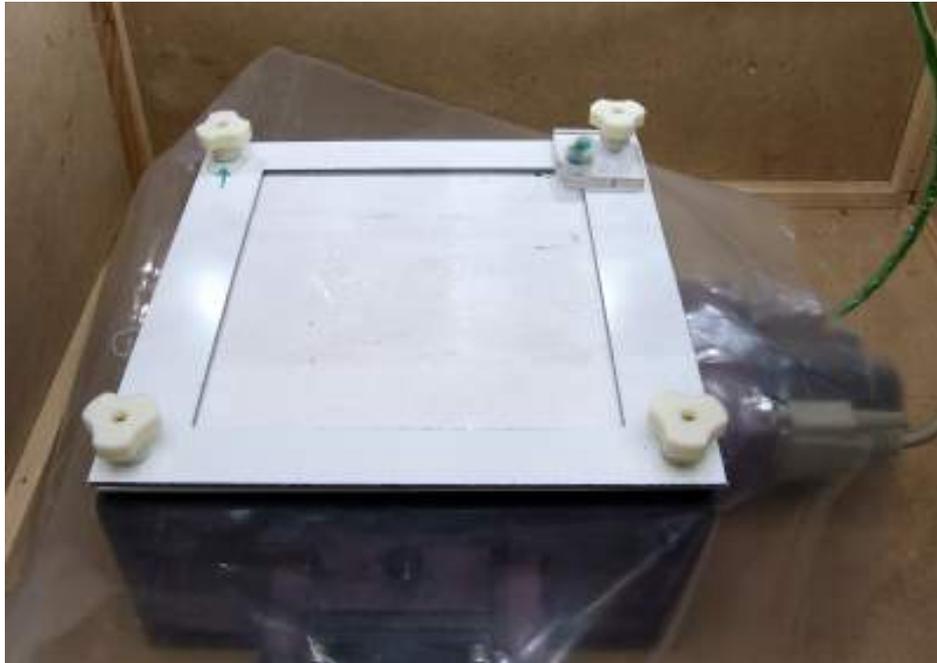
Easy to design, but the hexagonal cavity is a pain to model in ArtOfIllusion. You have to start with a six sided polygon. You then convert it to a triangle mesh and then extrude it to make a hexagonal prism to subtract from the cylindrical shaft.

The three types of solid primitive: cube, cylinder and sphere all have editable dimensions but for some reason polygon primitives don't show any dimensions. To get round this you have to set the grid spacing to the dimensions you want and snap the polygon's bounding box to the grid.



I intended the nuts to be a push fit but they were too tight so I pushed them in with a hot soldering iron. The small M4 one on the left was a test to see if the design scales. I think the nut cavity needs to be a bit shorter for metric nuts.

These cost less than \$0.06 each in plastic so that saved me \$5.76. A good example of the economics of RepRap. Although it is no doubt cheaper to make wingnuts by traditional means in large numbers, the cheapest way for an individual to obtain them in small quantities is to RepRap them. Of course I needed some plain nuts, but they are a lot cheaper and easier to obtain.



# Alternative alignment

Monday, 23rd June 2008 by Nophead

The Darwin build [instructions](#) recommend squaring up the frames by adjusting the corner blocks to get the correct length stubs sticking out as the excerpt below shows: -



Image not found.

This assumes that the rods are exactly the same length. I think what is actually important is that the gap between the rods is exactly 400mm. To achieve that I made a temporary jig from a couple of diagonal tie brackets and a piece of the 8mm rod and adjusted it so that the outside of the brackets was 400mm. I then used that to space all the rods of the lower frame. I also set the short stubs to 20mm using the first method above. Any variation in rod length then ends up on the the 28mm stub.



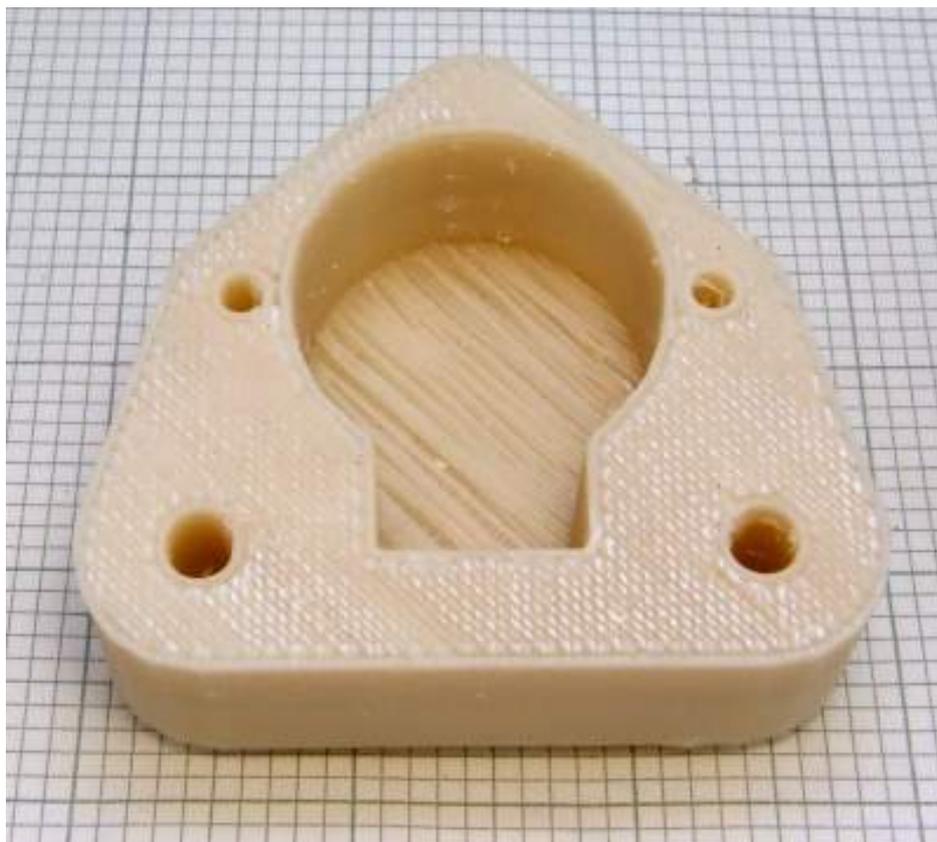
# Spanning a void

Thursday, 26th June 2008 by Nophead

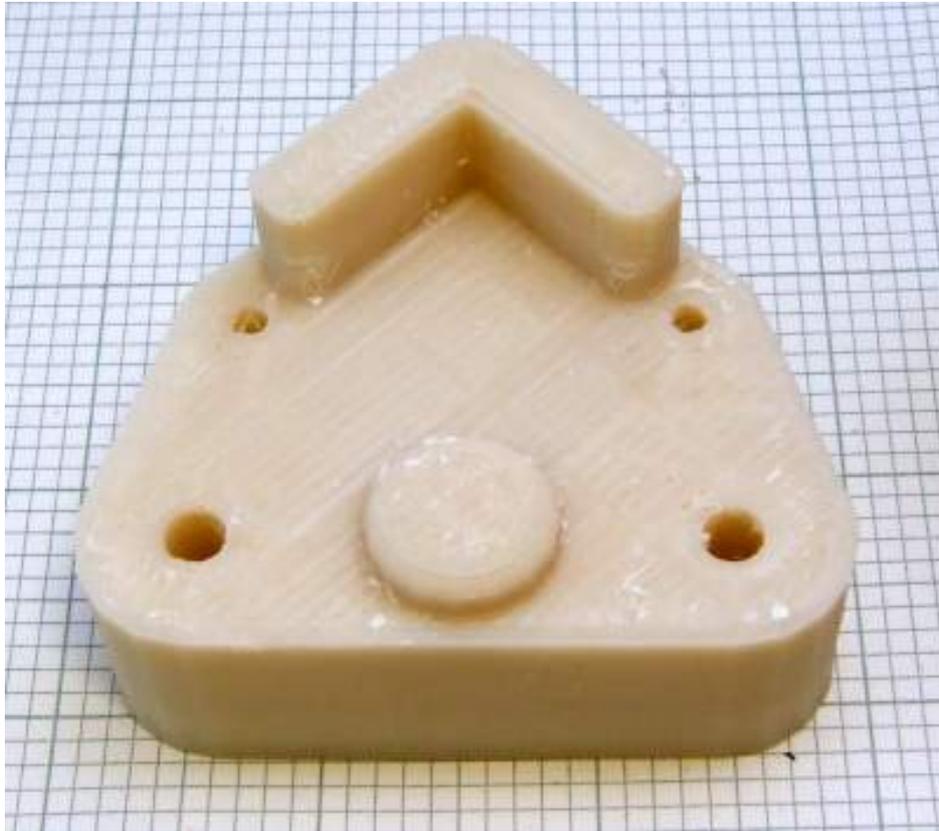
s0lstice requested that the next time HydraRaptor was extruding into fresh air I should post a video, so here is a video of a part with a large covered void being made: -

Spanning a void from Nop Head on Vimeo.

It is a bracket to mount a tiny stepper onto a Darwin corner bracket.



As you can see, the unsupported layer is very untidy, but the next layer sorts itself out. The reason I had to make this side the top is that there are projections on the bottom to mate with the corner bracket: -



Here is what it looks like installed. I need to sort out a shaft coupling. I have no idea if the motors will be powerful enough though.



I also made some feet for my Darwin to stop it scratching the table: -

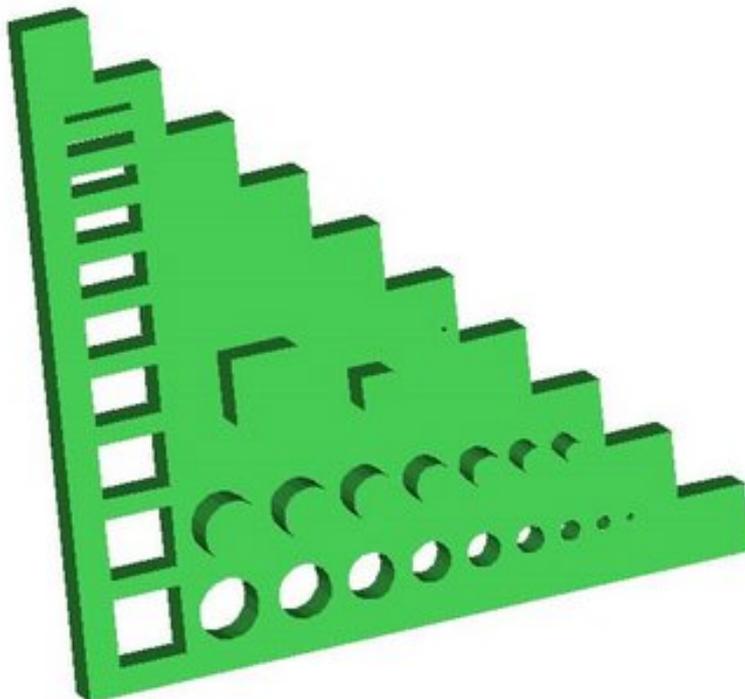


I stuck felt pads, that I happened to have, on them, but rubber would probably be better for non slip.

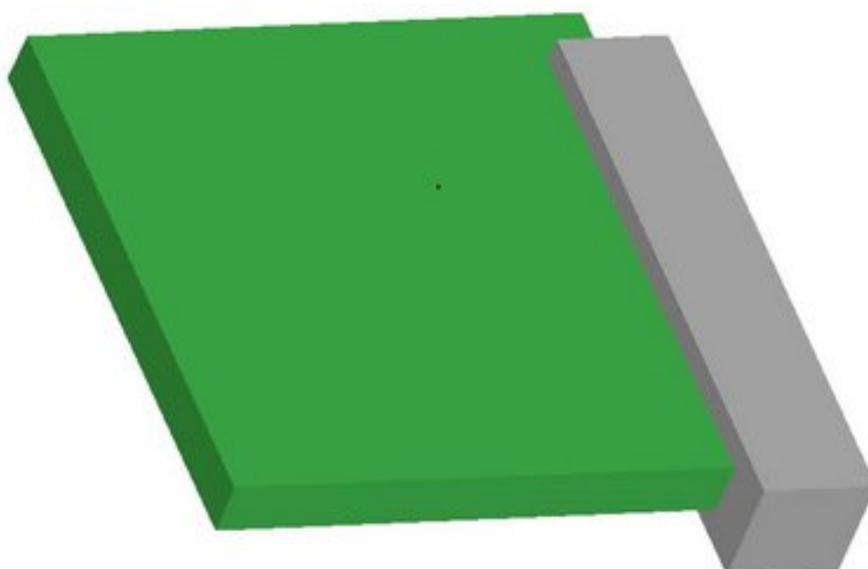
# From illusion to creation

Saturday, 28th June 2008 by Nophead

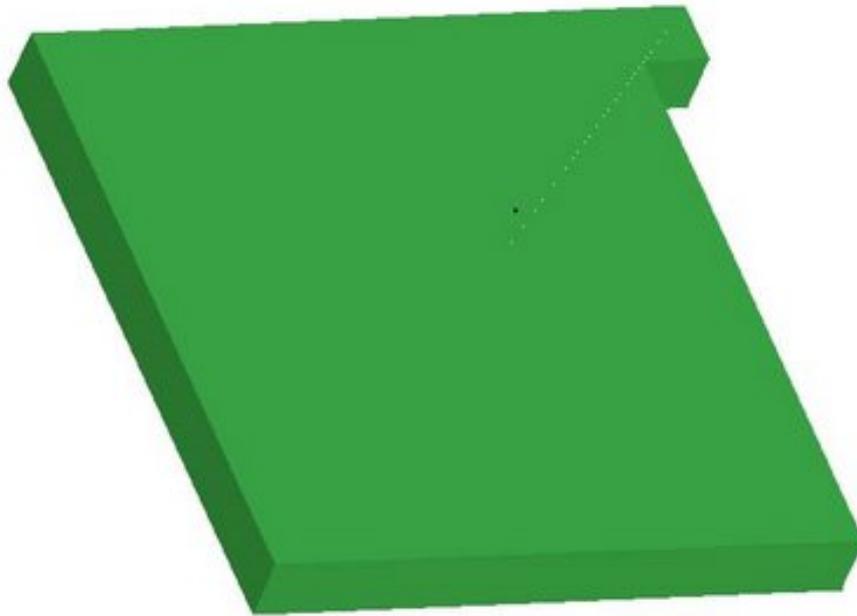
A few days ago I spent a frustrating evening trying to create this test shape in ArtOfIllusion: -



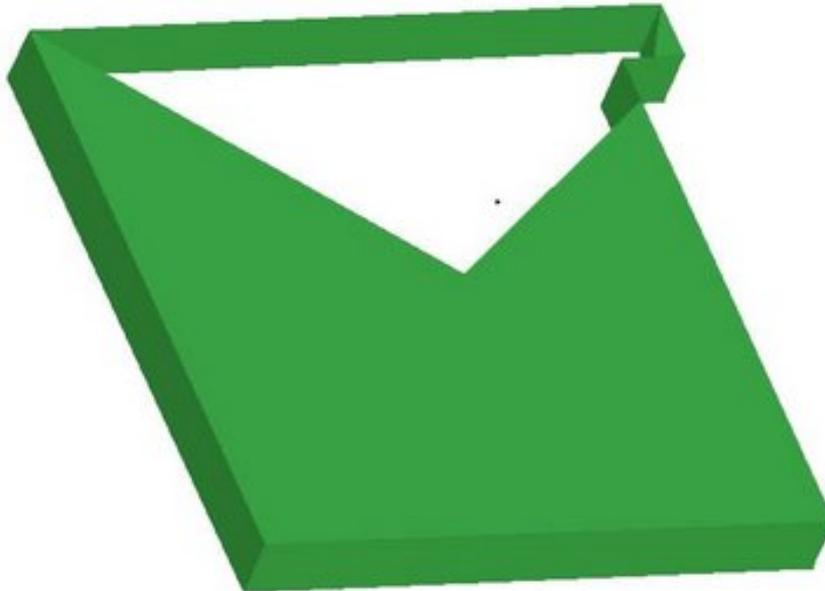
No matter what I did, I could not get a manifold object that could be exported as an STL file. Eventually I reduced the problem to the fact that AOI cannot do a simple boolean subtraction of two rectangular cubes correctly.



The result looks OK but it is non manifold, I think some of the triangles are the wrong way round.



Fixing it with the Solid Editor produces this: -



So AOI is not really usable for engineering. It is open source, so theoretically I could fix it myself, but life is too short to fix my own bugs, let alone other peoples. I posted a [bug report](#) and moved on.

Speaking to one of my colleagues who does mechanical design for a living, it would seem that professional tools are much easier to use and you don't have to worry about operations on coincident faces, etc. He recommended [CoCreate Modeling Personal Edition](#), which is free for non professional use. It is limited to 60 parts in one design and can only save designs in its own proprietary format, but it can export STL and VRML. It is Windows only and needs an internet

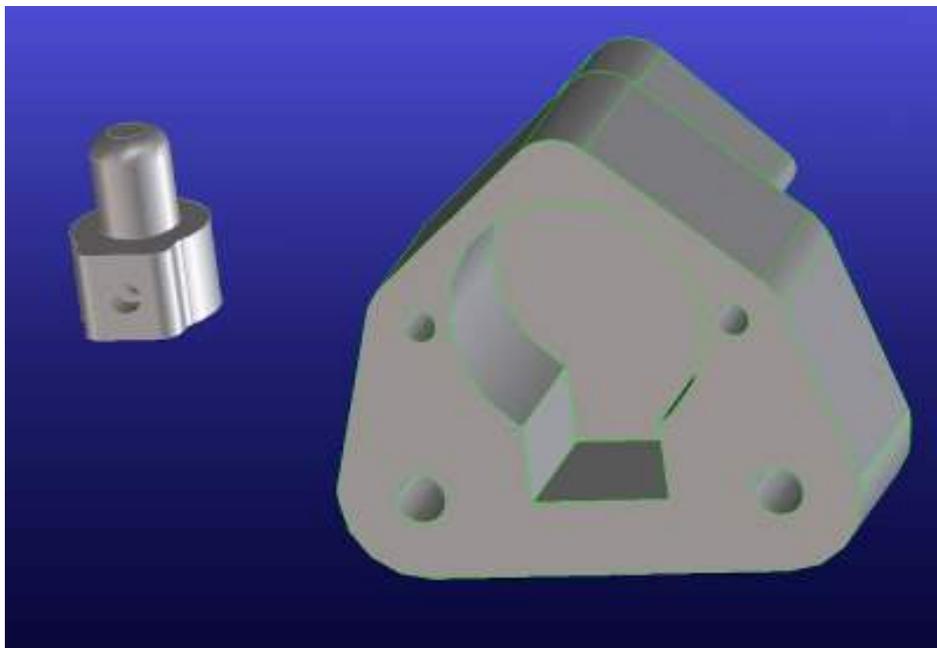
connection every three days. It is however, very easy to use. I had a quick look at Google Sketchup and Blender but they did not seem as easy.

The way you model in CoCreate is that you start by drawing in 2D on Workplanes. Workplanes can be arbitrary, but generally are created on a face of the part you are building. The 2D drawing tool is called CoPilot. It shows lots of hints when lines are parallel or line up with things already drawn, and shows dimensions to nearby features. This makes it very easy to create 2D geometry with precise dimensions, or geometrical alignments. You can also draw construction lines to help you line things up.

When you have a 2D profile on a Workplane you can then Extrude it or Turn it to make a solid. This is similar to AOI, except that the 2D drawing in AOI is very primitive and it is hard to get exact dimensions. As well as adding material you can remove it with familiar machine operations like Mill, Bore, Punch, Stamp, Section and Shell. These would all take multiple steps in AOI. CoCreate also has the boolean operations: Unite, Intersect and Subtract, but whereas you have to do almost everything in AOI with booleans, I have not needed to use them so far in CoCreate.

Once you have your basic 3D form it is very easy to add chamfers, fillets, blends, etc, and surprisingly it is also easy to remove them again.

Nothing I have done so far, (including filling a hole with a cylinder of the same dimensions), has managed to create a non manifold shape. It is very quick and easy to make practical objects. Here are a couple of parts I modeled for my experimental z-axis as they appear on screen: -

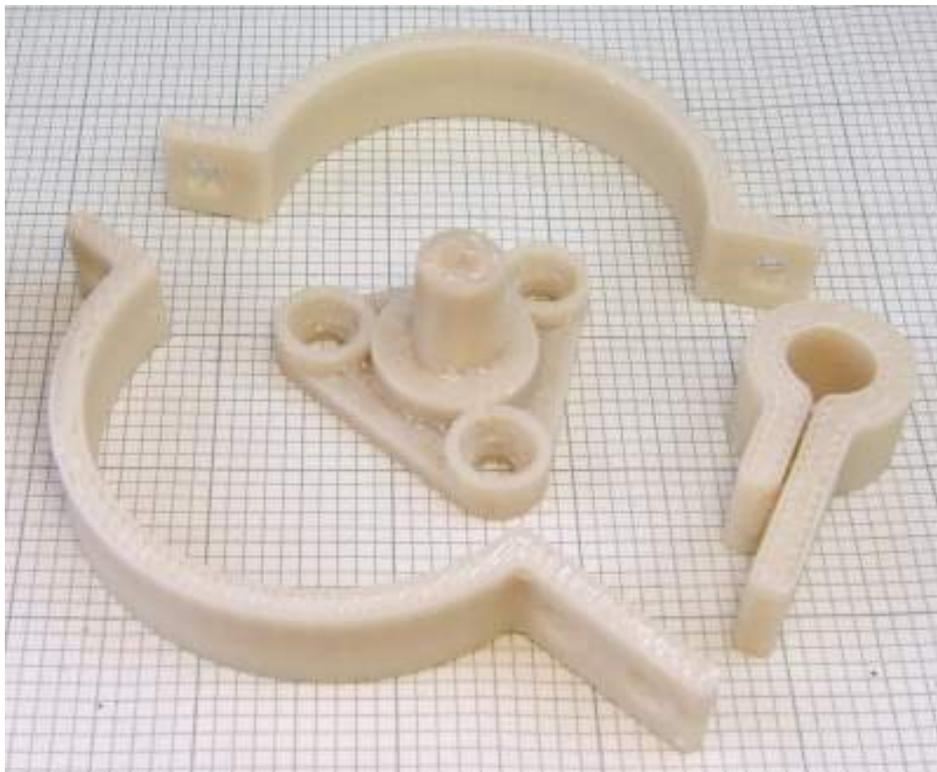
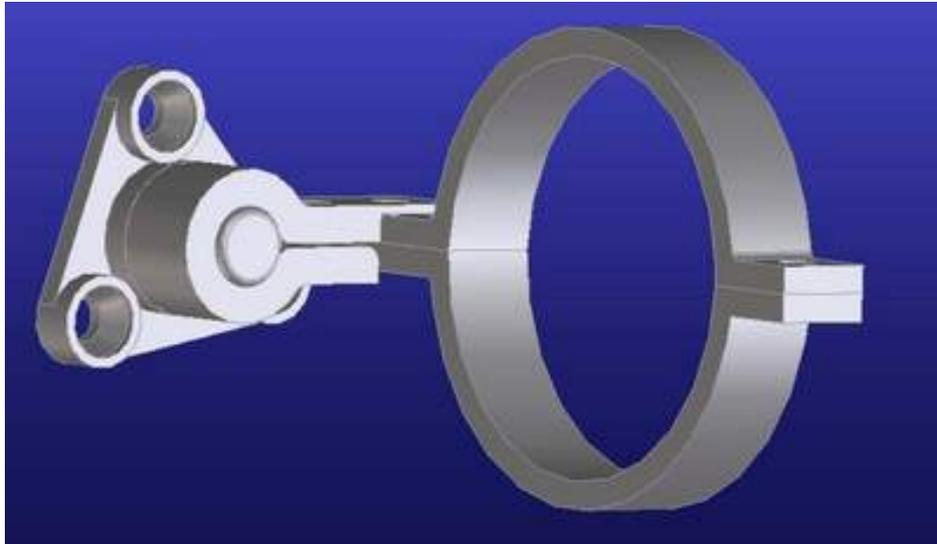


I have no idea how I could have created these in AOI.

# Bespoke bracketry

Sunday, 29th June 2008 by Nophead

A friend of mine makes underwater cameras from plumbing accessories so that he can observe the fish in his pond. He needed a bracket to hold a piece of pipe with an adjustable tilt angle so he asked me to make one. Here it is: -





I don't know how long ABS will last in a pond, but as long as it is years rather than months it is no trouble to print it again.

# Deviant Z axis

Friday, 18th July 2008 by Nophead

The RepRap Darwin Z-axis has four screw thread drives linked by a timing belt and toothed pulleys, driven by a large stepper motor.

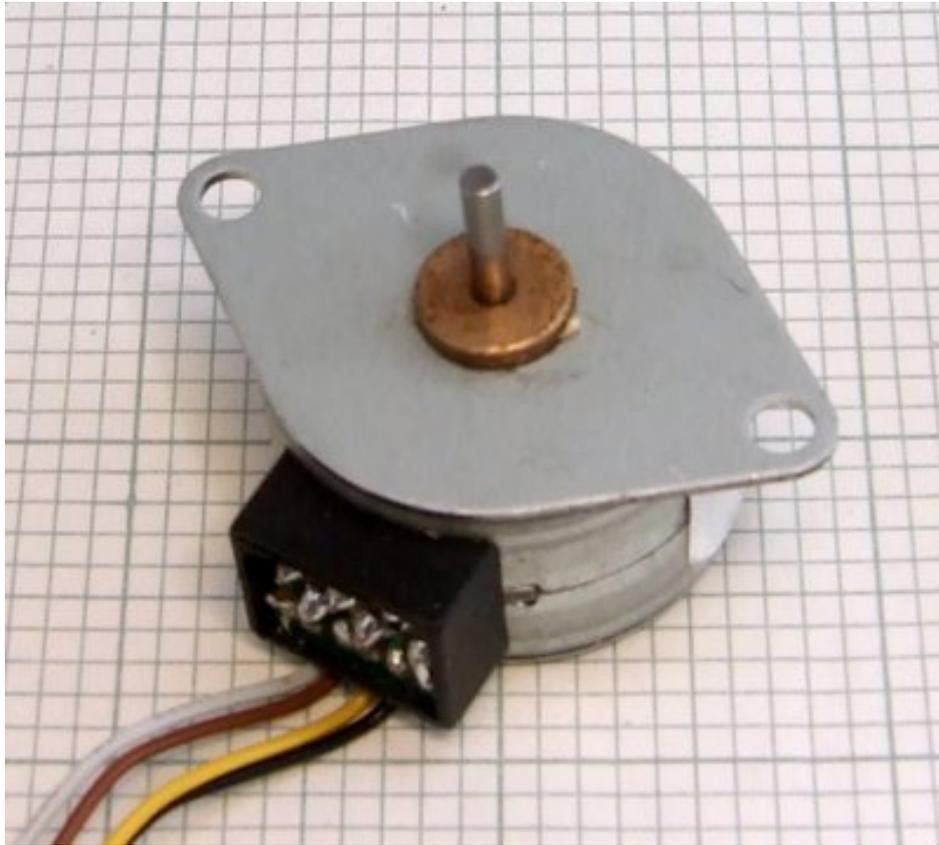


Image not found.

There are a few things about the design that I am not keen on: -

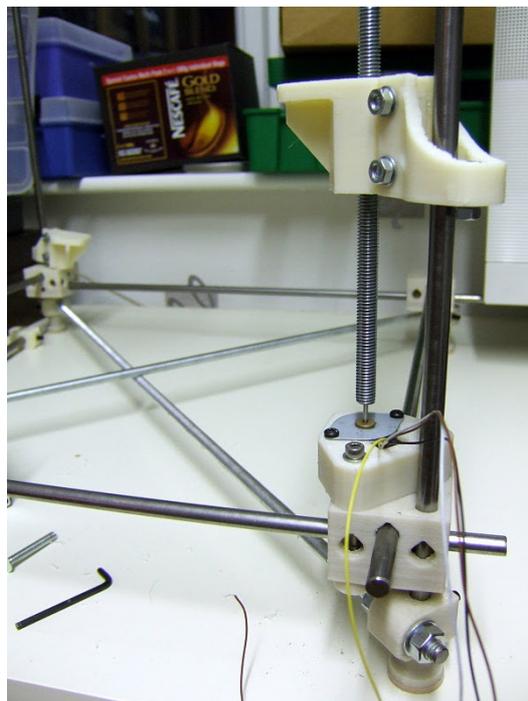
- The beefy motor and timing belt make it expensive.
- The belt tension puts lateral force on the threaded rod, which causes a lot of friction and looks like it will cause the plastic bearings to wear.
- Making the pulleys and splicing the belt seem like tricky things to get right.

When Forrest Higgs came across a small fast stepper motor I decided try an alternative scheme using four motors wired in parallel, eliminating the pulleys, belt and lateral forces. The four small motors are about the same price as the big one, so the cost of the timing belt is saved.



When the motors arrived I got a bit of shock at how small they were. Although I had seen photos from Forrest's blog they were about half the size I had imagined. They are lowish inductance and large step angle ( $15^\circ$ ) so they can go very fast.

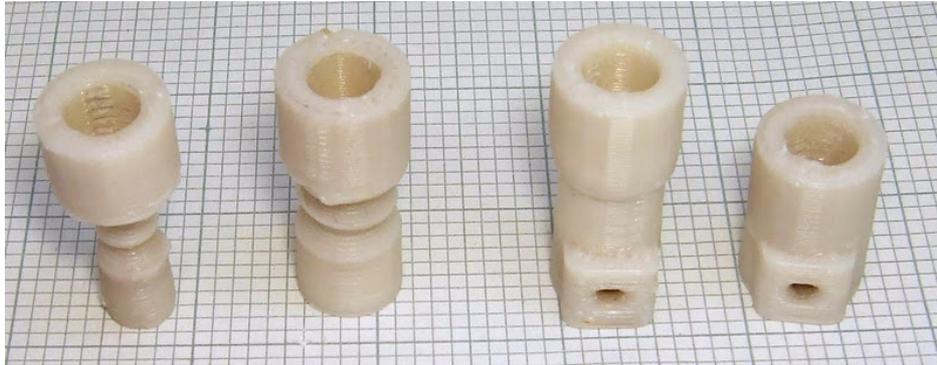
I designed a bracket to hold the motor and mate up with the Darwin corner bracket: -



As you can see there is vast discrepancy between the shaft sizes and one quarter of the weight of

the table is born by each of the tiny motor bearings. I was starting to get a bad feeling about the idea.

I had several unsuccessful attempts at making a flexible shaft coupling from ABS: -



None of these were flexible enough or concentric enough. My final design used a piece of plastic piping to get the flexibility.

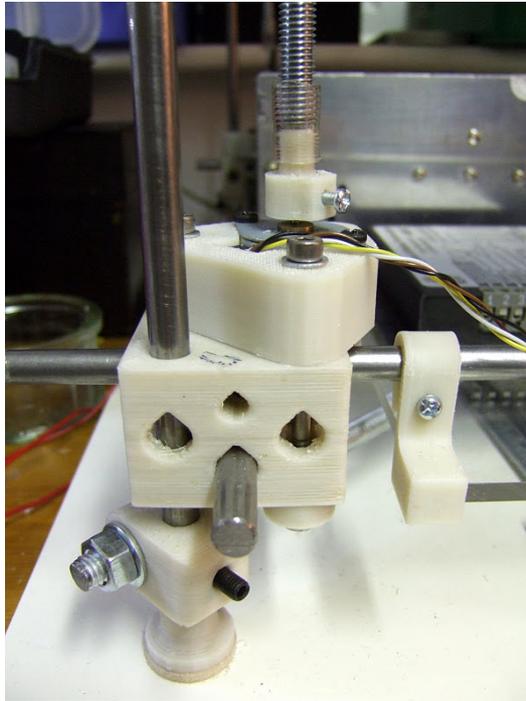


It has a captive nut for the M3 set screw. The piping is just a friction fit and the rod screws into it.

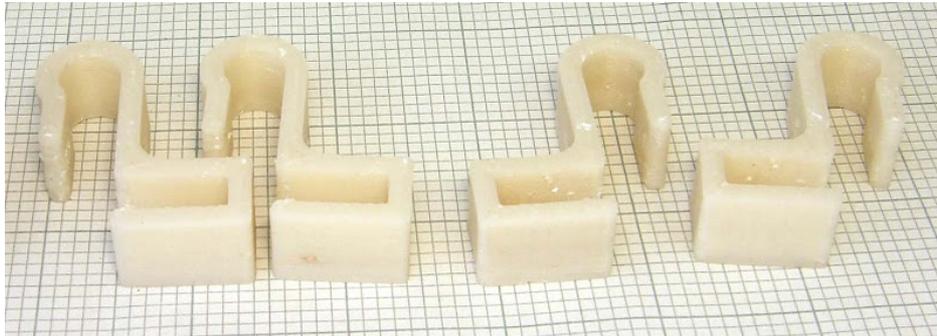
Even with this design I had a problem with the eccentricity of the hole for the motor shaft. When you make a hole with fused filament fabrication, the outline of the hole has a start and an end. This causes a bump in the perimeter. Possibly, the outline should end one filament diameter short of where it started, rather than being a full circle. Also each layer should start and end in a different place. When I get chance I will try this.

To remove the bump I ran a drill through the hole. When the hole is as small as this (2mm) the bump displaces the drill leaving the resulting hole off centre. I ended up having to drill them on the lathe, which is cheating.

I mounted the four motors and wired them up in parallel to a micro-stepping chopper drive and a 36V power supply.



I don't like the RepRap scheme of distributing the electronics around the machine so I mounted mine all together at the bottom of the machine on a sheet of perspex. The perspex rests on one of the base diagonals and is held in place by four brackets which clamp around the lower frame.



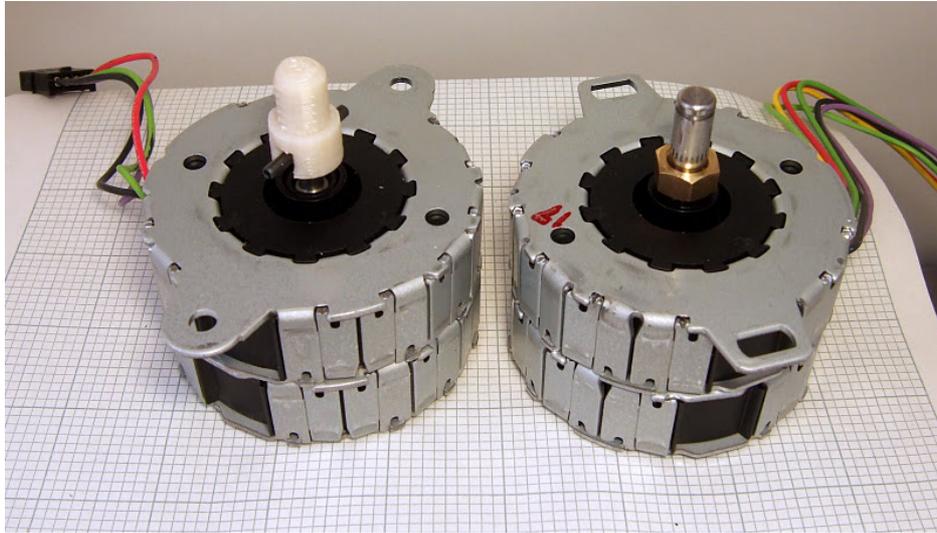
As soon as I powered it up I realised that the motors had nowhere near enough torque to turn the M8 threaded rods. It wasn't a big surprise, two things that were though:

The motors got ridiculously hot, well over 100°C before I switched them off. The coil resistance is 27  $\Omega$  which is smaller than some much larger 12V motors, giving a dissipation of about 10W. These look more like 5V motors to me, either that or they are not continuously rated.

I found that my micro-stepping drives don't work well with tin can motors. The micro-steps are very uneven in size. Micro-stepping assumes that the torque displacement curve of the motor is sinusoidal, which doesn't seem to be the case for large step angle tin can motors. Not a big problem in this case as I don't need the extra resolution. I will replace the drive with something simpler when I have got the machine working.

So all in all a big failed experiment! I should have wired up one of the motors before I wasted the plastic making all the mounts.

My fall back plan was to use some larger tin can motors I rescued from a skip recently.

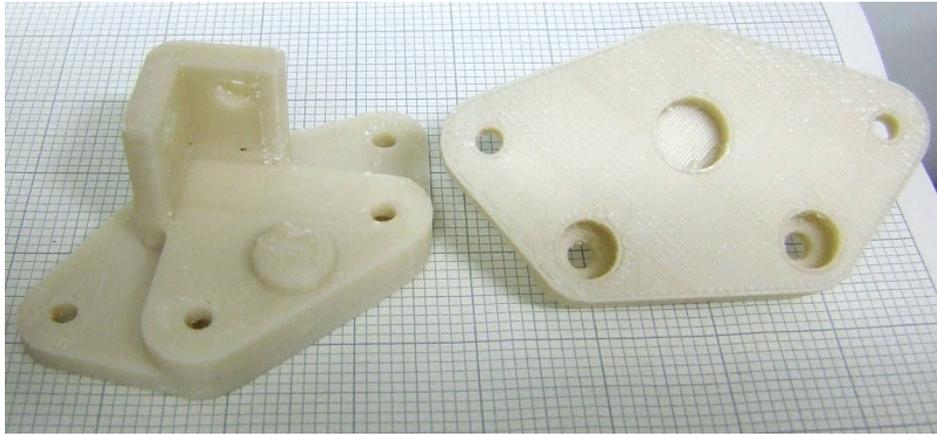


The one on the left is bipolar and the one on the right is unipolar. I decided to try the bipolar ones first, I may switch to the unipolar to simplify the electronics, if they have enough torque.

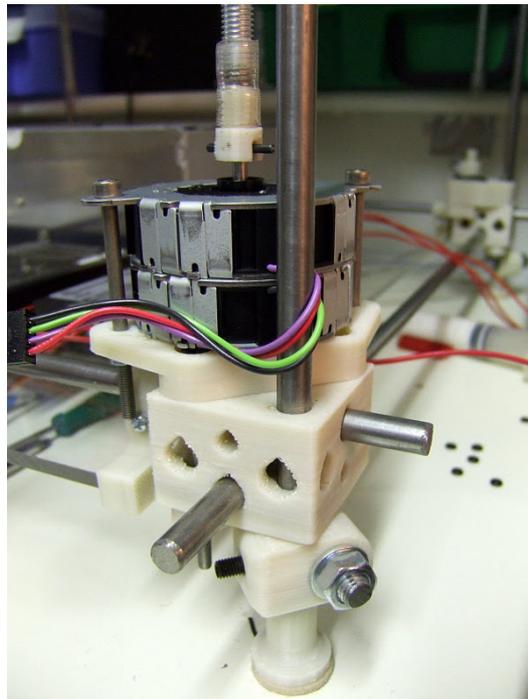
The shaft coupling was much easier to make because the shaft is bigger (4mm) and has a pin through it. I didn't need to resort to the lathe this time.



I designed and made a new set of motor brackets, they took about 8 hours to print in total.



Here is one motor installed: -



It seems to have plenty of torque for the job. I am waiting for more bolts to arrive to mount the others.

These are not low inductance motors so they won't be as fast as the original single motor design. The large step angle ( $7.5^\circ$ ) and my 36V supply will help to mitigate this. I originally thought the z-axis speed was unimportant because it moves so rarely, but actually on HydraRaptor I use the z-axis to lift the head 0.4mm when moving between filament runs so it does need to be reasonably quick.

This scheme certainly simplifies the mechanical construction but may not make economic sense. The motors are cheap in large volume (£2-3) but I haven't found a retail price.

# A bit of a contraption

Thursday, 24th July 2008 by Nophead

As I was adding the diagonal tie bars my wife said "it's becoming a bit of a contraption". I am not sure if that is a good thing or a bad thing!

My alternative z-axis using four tin can stepper motors works reasonable well. I am running them from 36V with a constant current chopper drive. They are all wired in parallel and the total current is set to 1.25A. They have 22 coils so that corresponds to about 7V. I am guessing they are rated for 12V, but if you run steppers at their maximum rating they get very hot, especially when mounted on plastic rather than a metal chassis. Under running them, as I am, they only get to about 40°C, which should be fine even for PCL and PLA brackets. Total power used by the axis is about 9W.

The standard Darwin z-axis can carry a small child: [regrap-prints-child](#). Not having any small children, I tested it with a vice that weighs 3.3Kg. As it would take 300 hours to print anything that size so I think it is a reasonable worst case test.

The pull-in step rate (i.e. the maximum rate that the motor will start at with no acceleration) is about 400 steps/second. It runs reliably at 320 steps/s, which is 8.33 mm/s. If I understand the [settings page](#) on the wiki then this is more than 10 times faster than people are running the belt drive version. Still much slower than HydraRaptor's z-axis though.

Here is a video of it in action: -

[Alternative RepRap Darwin Z-axis](#) from [Nop Head](#) on [Vimeo](#)

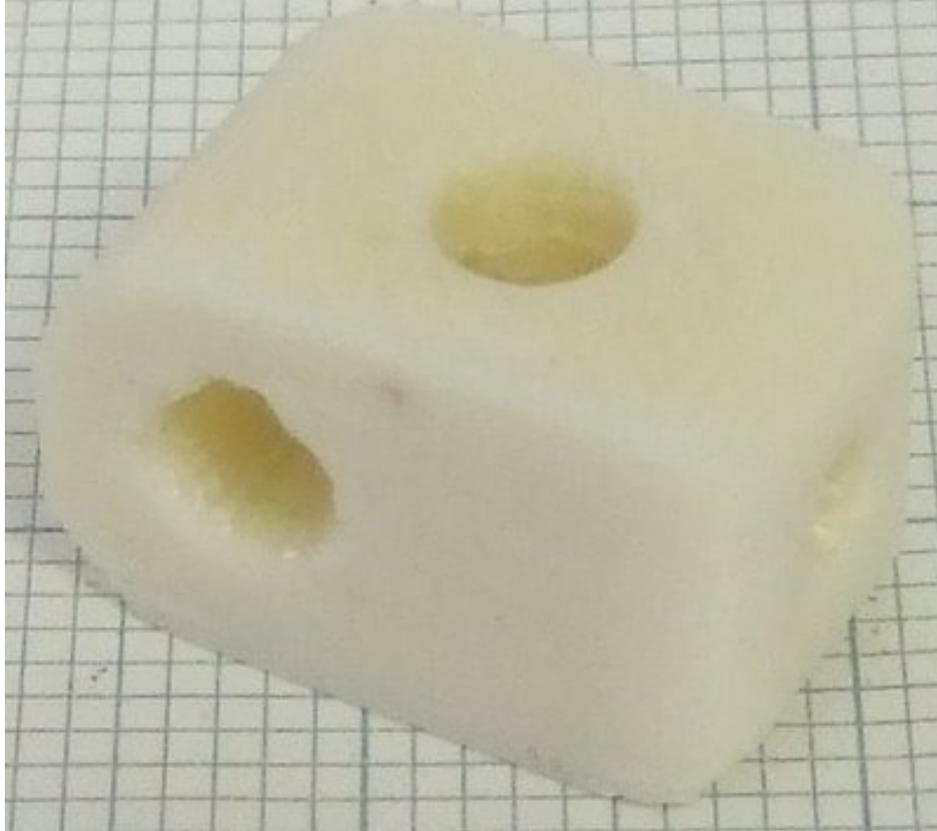
As you can hear, it doesn't make a lot of noise, something that is a big improvement on HydraRaptor, which has a very noisy z-axis.

The total travel is 230mm, which is also a bit better than the standard Darwin I think, but you have to subtract the length of the extruder barrel to get the maximum work height.

# Every little helps

Saturday, 26th July 2008 by Nophead

The RepRap Darwin design has 10 diagonal tie bars across the corners of all but the top face of the cube, making it very rigid. These are attached by 20 diagonal tie brackets.

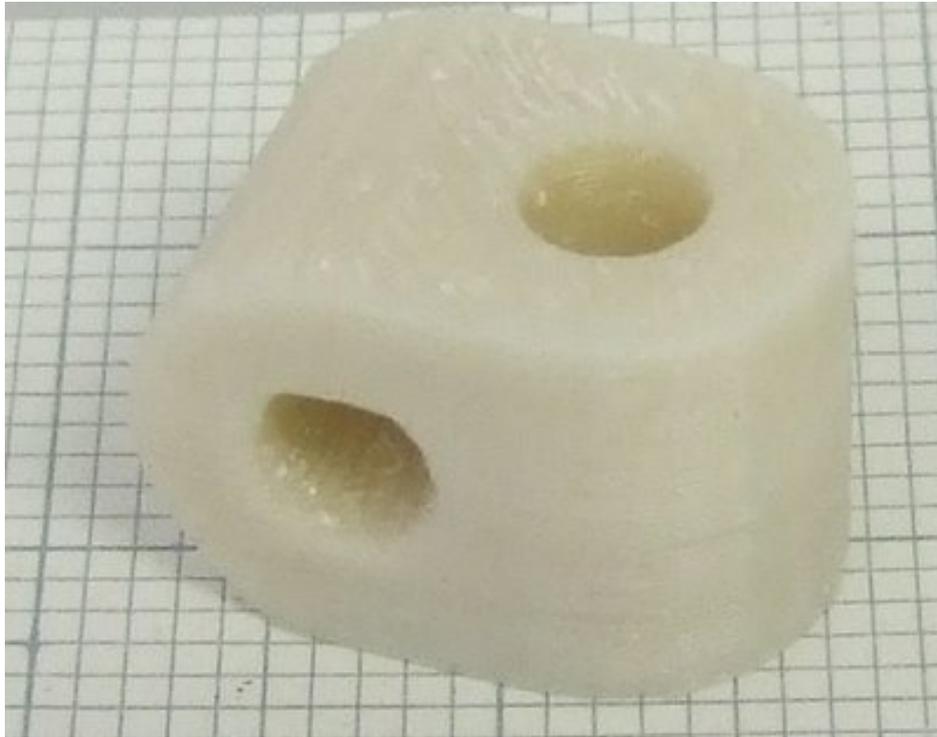


The brackets are held onto the protruding 8mm stubs by M5 set screws through a captive nut. The diagonal bars are then held in place by M8 nuts either side of the bracket.

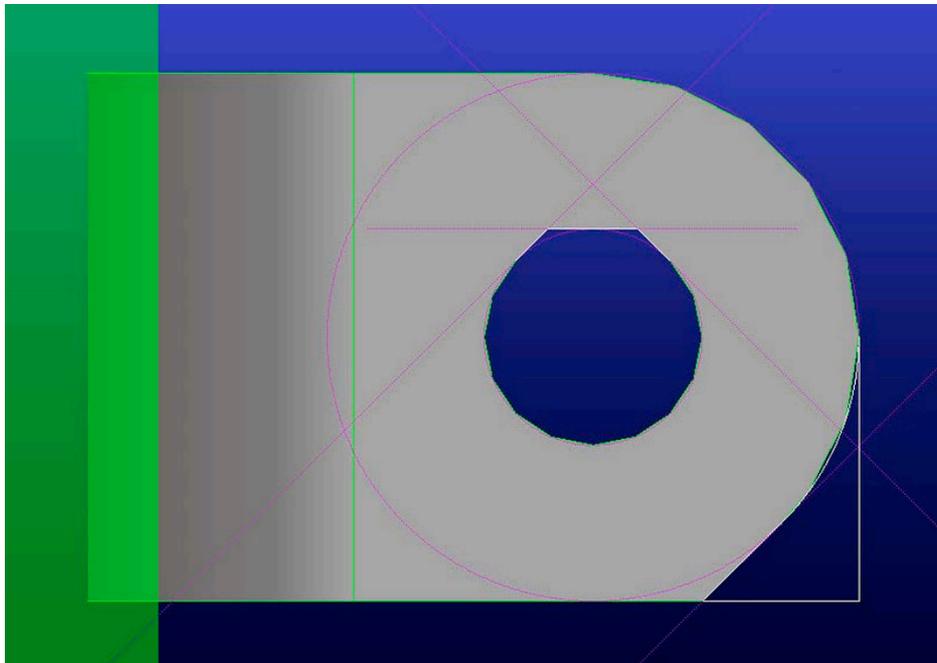
When fitting them I noticed that the set screws and nuts are not necessary. All the holes I make come out a little undersized and stringy so I clean these out with an 8mm drill. This makes them an interference fit onto the M8 rods. The force exerted by the M8 nuts is enough to squeeze the bracket to make it a tight fit. This is the case when they are made from ABS with 25% fill. Other plastics may be too strong or brittle.

This shortcut saves 20 grub screws and nuts and the time to fit them (inserting the nut can be quite fiddly). Not only that, the bracket can be simplified and made smaller because it does not need space for the nut and grub screw. This optimisation is well worth doing because, although these brackets are quite small, there are 20 of them so they are a significant part of the time taken to replicate.

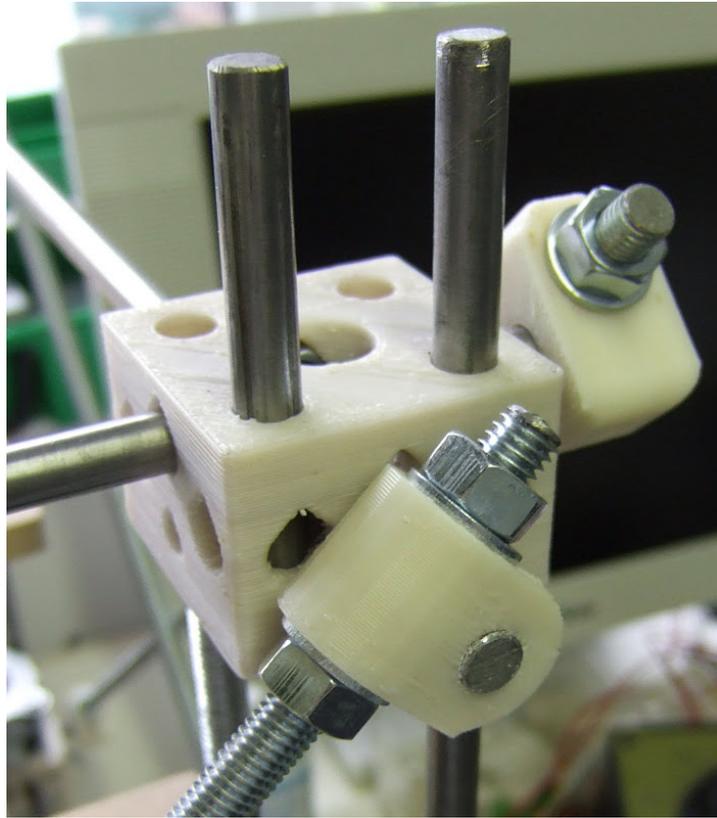
Here is my smaller design which uses 21% less plastic and reduces the time to make 20 from 11.5 hours to 9 hours on my machine :-



I also used a truncated teardrop for the lateral hole. This relies on the fact that filament can span gaps as well as being able to build out at  $45^\circ$ . The drawing below illustrates that, even for an 8mm hole, the difference between a proper circle, which would require support material, and this truncated shape is very little. It also shows where the full teardrop would extend to.



Here is a picture of it installed alongside the old design: -

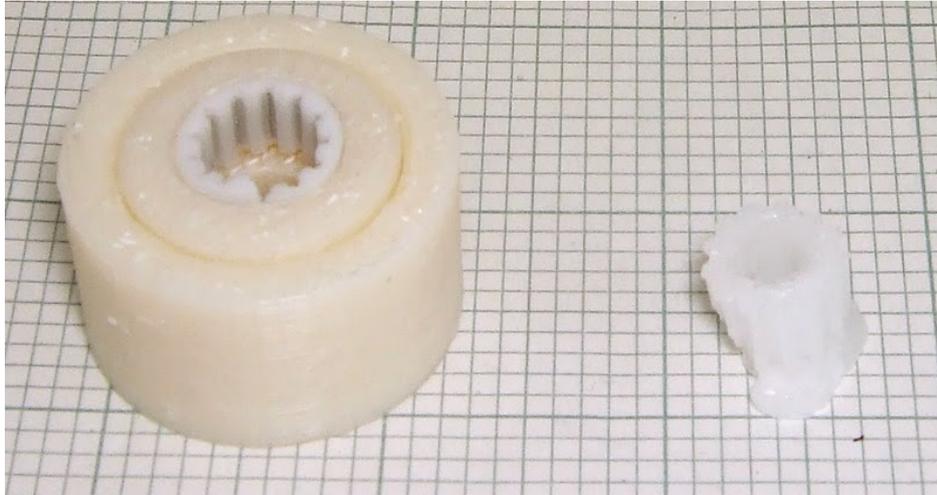


I think this is a beneficial mutation that will slightly increase the rate at which Darwins reproduce in the wild. The new DNA can be found [here](#).

## X & Y

Tuesday, 5th August 2008 by Nophead

I have finished building my Darwin Cartesian bot. It went together fairly easily although I did cheat when it came to making the pulleys. The idea is to cast toothed pulleys in PolyMorph using a mould made from RP components and lined with a piece of belt. I had one go at this and decided it was not going to produce an accurate result: -



The RP mould, when made on my machine, is not round enough and for some reason the diameter of the mould is too small, making the resulting pulley very thin walled and flimsy. It produced a 13 tooth pulley but 16 teeth is the correct number for 0.1mm per motor half step and makes a chunkier pulley. I bought three aluminium ones from Farnell for £5.90 each: -



These are ridiculously expensive for what they are but I think it is worth spending a bit of money in an area that increases accuracy. It is also one of the few places where the accuracy of the parent machine affects the accuracy of the child.

The big problem is that they only have a 4mm hole in them so you have to bore out the x-axis one to 1/4" and the two y-axis ones to 8mm. To do that accurately really requires a lathe. As mine is only a tiny watchmaker's lathe I had to use every drill from 4.5mm to 8mm in 0.5mm steps. I found that dipping the drill bits in Treflex cutting compound made it much easier to drill. This was recommended to me for tapping but it great for drilling as well. It is a sort of jelly, so not too messy.

When you use a twist drill to make a hole it comes out a little small and not perfectly round. It needs to be finished off with a reamer to get a nice fit onto the motor shaft and the 8mm rod. I happened to have a 1/4" reamer but I had to improvise for the 8mm ones with a piece of emery paper wrapped around a 7mm drill shank. Not ideal, so I ordered an 8mm reamer as I expect I will be making lots of 8mm bearing holes in the future.

I also had to drill and tap M3 set screw holes in the pulleys. Easily done with a drill press and it means I don't have to file a long flat on the y-axis drive shaft.

I tested the axes with a signal generator connected to the step input of my stepper motor drivers to find the pull in step rate, i.e. the maximum rate at which the motor will start with no acceleration. Here is the x-axis running at 150mm/s: -

[RepRap Darwin x-axis](#) from [Nop Head](#) on [Vimeo](#).

Any jerkiness seen is the video, not the axis, which runs very smoothly. The axis does not have the mass of the extruder on it yet but I have run it at the same speed with a reel of solder on top. I expect with a bit of an acceleration ramp, like I use on HydraRaptor, I will be able to get it to go two or three times faster. This is not too surprising because it is a similar design to a 2D printer carriage but with a much more powerful motor. It will be interesting to see what effect it has on stringing if I speed up the head moves from 32mm/s to 150mm/s or more.

I have the motors wired bi-polar parallel, which is the fastest configuration. The inductance is four times less and the voltage halved so I think that is 8 times faster than bi-polar serial. Added to that I am using a 36V supply instead of 12V and FETs rather than Darlingtons. The voltage on the motor will have gone from about 9V to about 36V, so all in all about 32 times faster current rise rate I think. I am using expensive drives but the only aspect I don't know how to do cheaply is anti-resonance, so unless I am stepping through the resonant frequency I should be able to recreate this performance cheaply.

The rated current in this mode is 3.4A per phase but I am only using 1A per phase at the moment so that they don't get too hot. Given that the average supply current from the 36V rail will be correspondingly less than this, it should be fairly easy to generate the 36V supply from 12V to keep to the original goal of using PC power supplies or car batteries. It would be good to use electronics that can boost the current while accelerating and decelerating.

Here is the y-axis running at 100mm/s: -

[RepRap Darwin y-axis from Nop Head on Vimeo.](#)

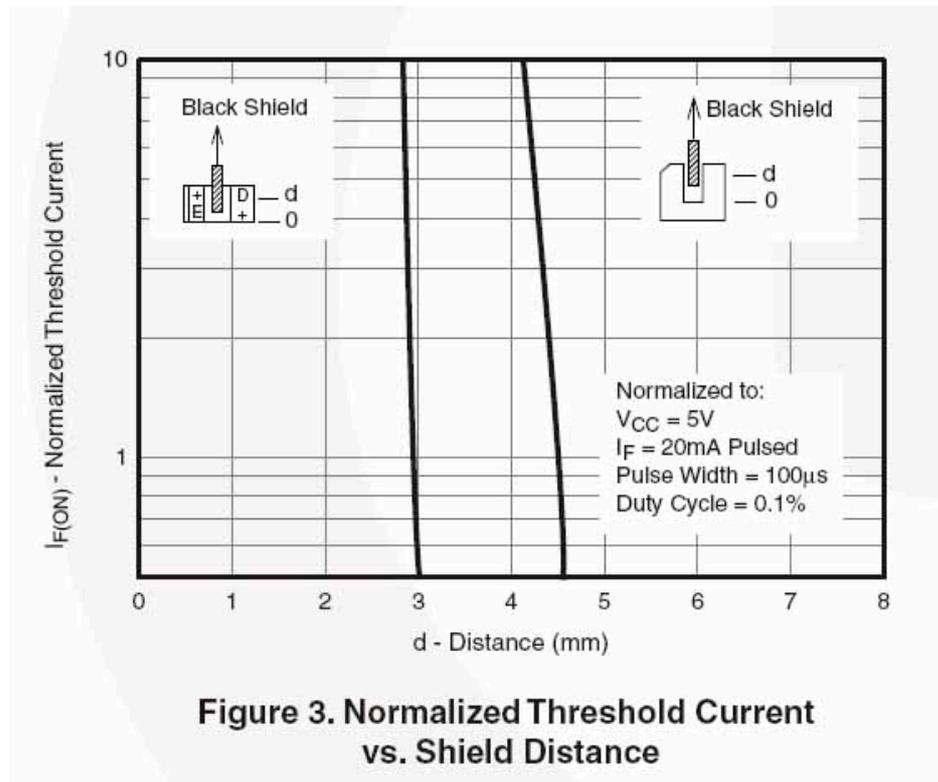
A few things I have noticed about the design that I would do differently: -

There is a bit of runout on the y-axis motor coupler leading to the shaft wobbling a bit and the motor bracket flexing to accommodate that. I think it would be better to have another bearing at this end of the shaft and a flexible coupling to the motor.

Several of the bearings are made with an RP insert, in my case ABS. I don't know how long these will last. I will have a go at making them from HDPE some time as that should make a better bearing and possibly replace the y-axis ones with 0608 skate bearings.

The rod that carries the Y-axis idler pulleys is held in place by tight fitting "jam" bearing inserts. I can't see the point of these, other than making all the y bearing housings the same. I would replace two of the bearing housings with a smaller part with an 8mm hole through it to carry the rod and possibly a set screw to lock it in place.

The X and Y axis opto tabs enter from the top. The opto has a 0.8mm vertical slit which is the optical aperture. A tab coming in from the side blocks all the slit at once making its resolution several times better than when the tab enters from the top. This graph, taken from the datasheet illustrates the difference: -



The z-axis opto endstop is at the top whereas I prefer to home away from the workpiece so that homing is always a safe operation when z is homed before x and y.

I will leave these tweaks until I have the machine up and running. All I have to do now is make a new extruder, hook my stepper drives to a micro and port my firmware. I will then have a Darwin that I can directly compare with HydraRaptor and see how it differs in performance. I will then look at replacing the electronics with something much cheaper.

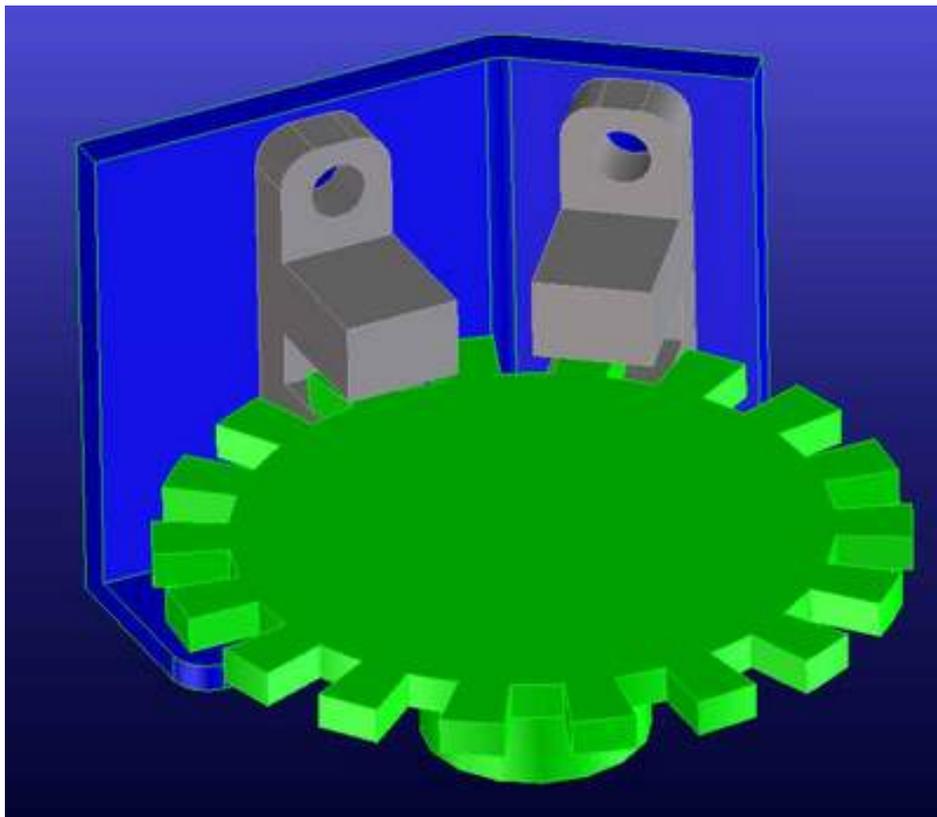
# RepRapped Shaft Encoder

Monday, 11th August 2008 by Nophead

I have started making an extruder for my Darwin but I am running out of ABS. I bought some more from [Tempatron](#) but it is very oval, up to 3.5mm, so it wont fit through HydraRaptor's extruder. So it is a race against plastic to make a new one with a bigger bore! I will try making the filament guide out of HDPE as that is the most slippery of the four plastics I have.

One thing I definitely wanted to try in ABS before it ran out was to make a shaft encoder. The latest RepRap [V1.1 design](#) has one with a single opto but it needs support material and gears. I am happy with the older design now that I have got it to run reliably, so I needed an encoder that mounts directly on the motor. I also prefer two optos in quadrature to avoid errors from backlash and stopping exactly on the edge of a slot. I want to experiment with backing up the filament as well, so I will make this version reversible.

I knocked up a design which uses a pair of slotted optos in CoCreate :-



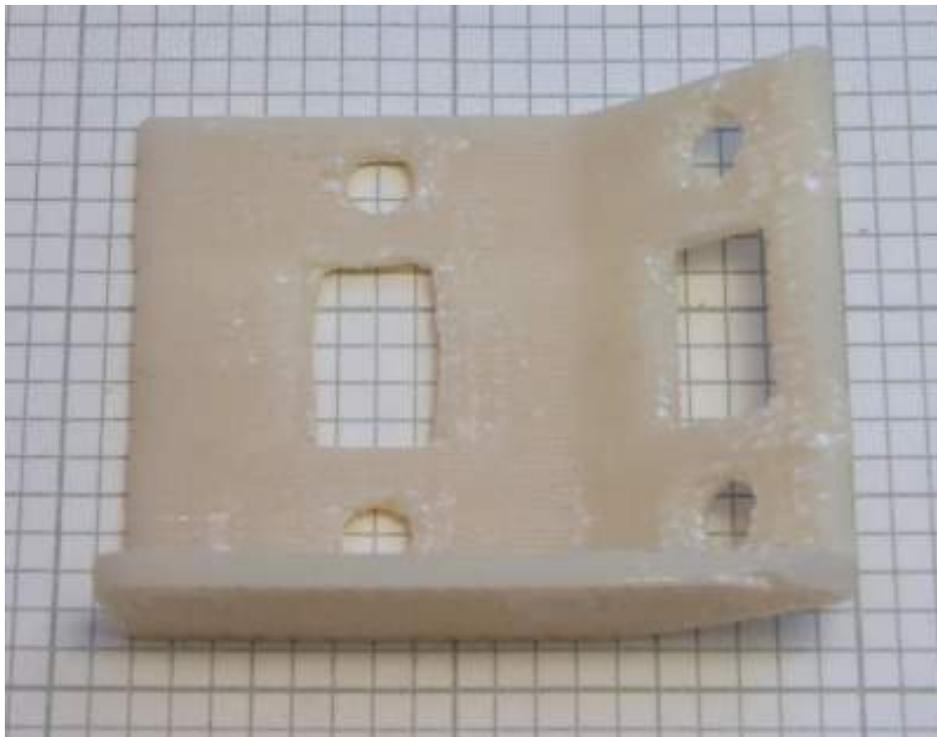
The wheel is the same as Ed's design except that I have added a boss which mates with the top shaft of the GM3 gearmotor. It has 18 teeth which gives 72 steps per rev with quadrature encoding. One turn of the extruder feeds 0.8mm of plastic with an M5 drive screw. That will extrude about 0.4mm of filament per step, so not great resolution.

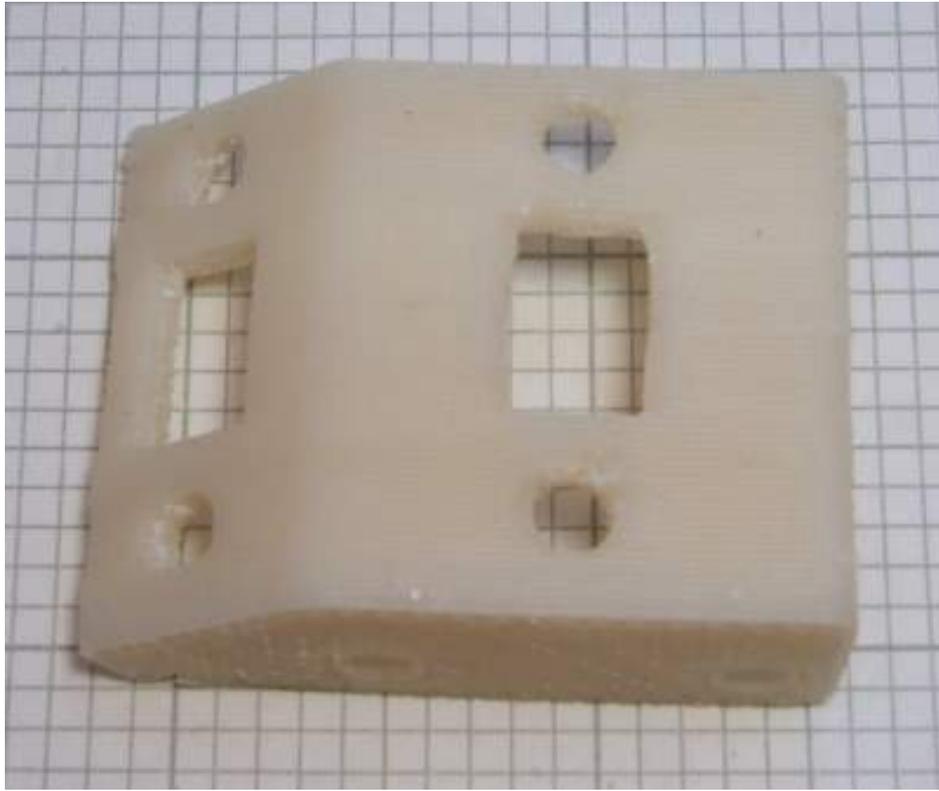
When making the opto flags for my Darwin I realised that quite thin walled objects come out OK

and are still reasonably strong. I think the bracket is the thinnest thing I have designed so far, its walls are only 2.4mm thick. Its shape really requires support material for the slots and holes but it came out fine without any. It was particularly hairy though when it came off the machine: -

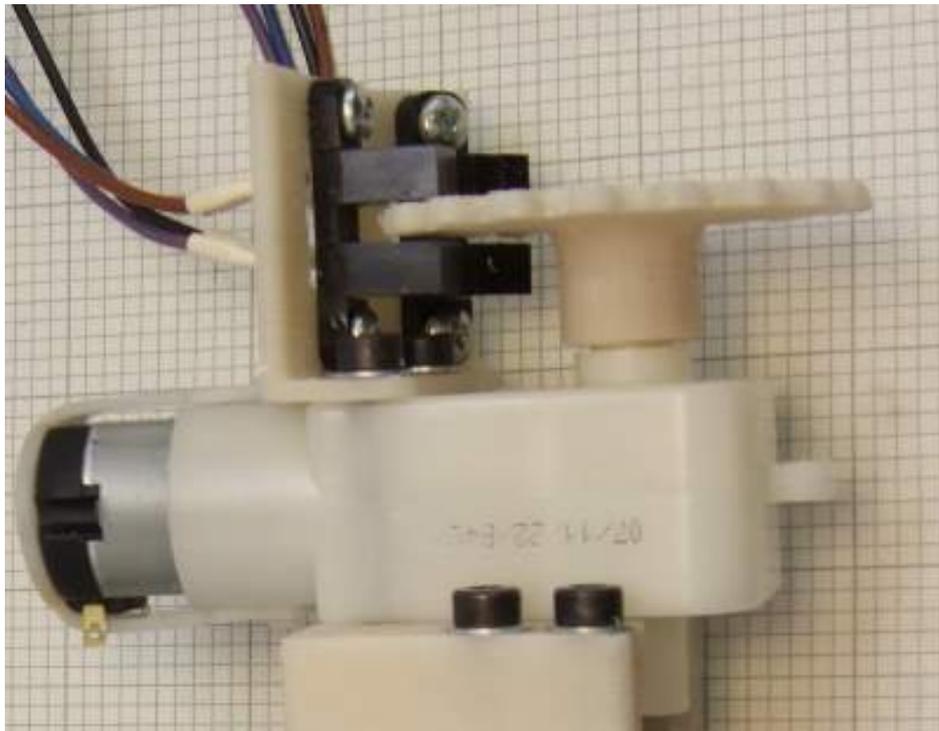


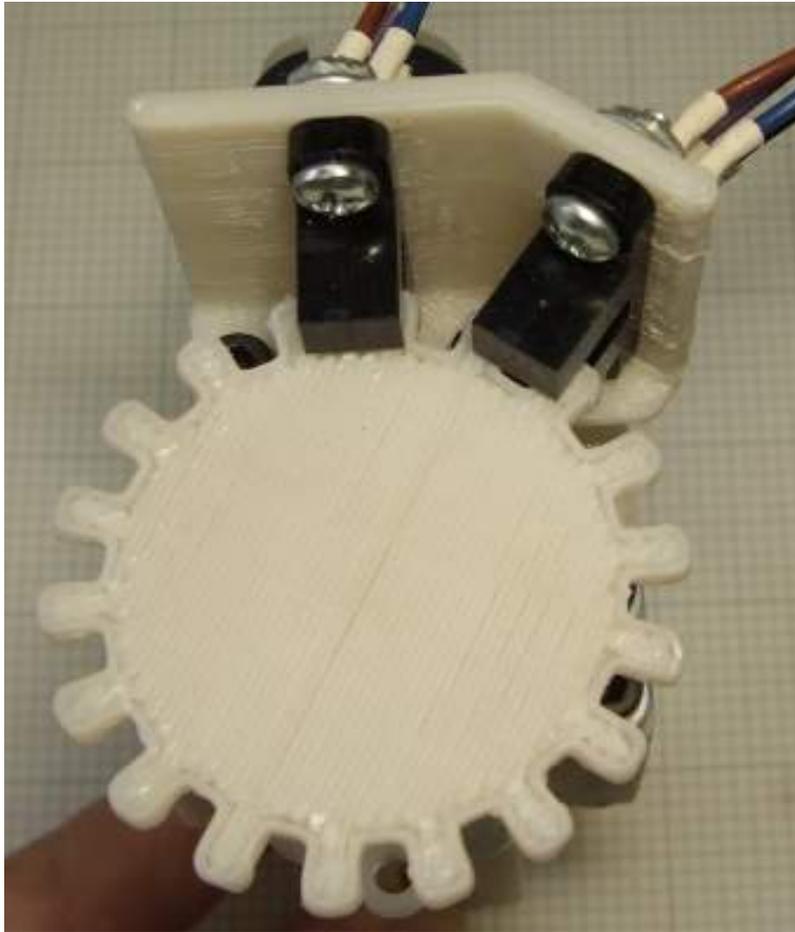
A bit of whittling with a penknife soon cleaned it up :-





Here it is installed on the motor :-

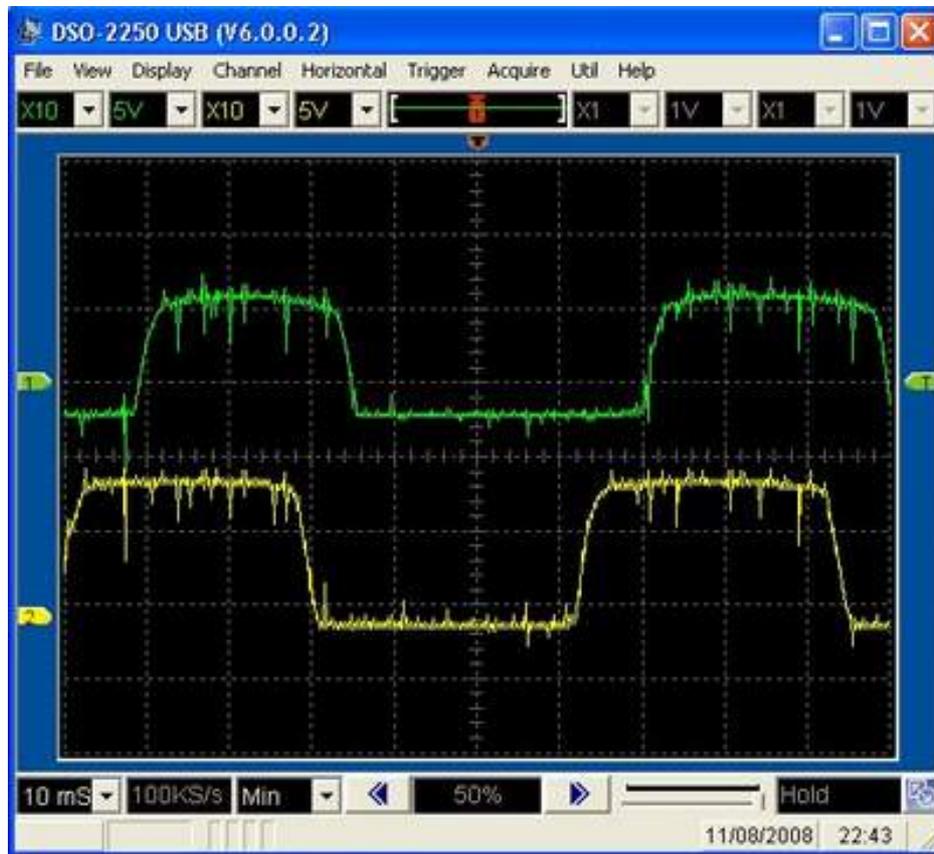




I wired up to an oscilloscope to test it: -



As you can it is very noisy because I have not made a new suppressor for the GM3 yet. Also the top trace does not go high properly. This is because quite a lot of IR light gets through the ABS when it is so thin. Not surprising as you can see visible light through it. I painted the top surface black with BBQ paint and that improved it a lot.



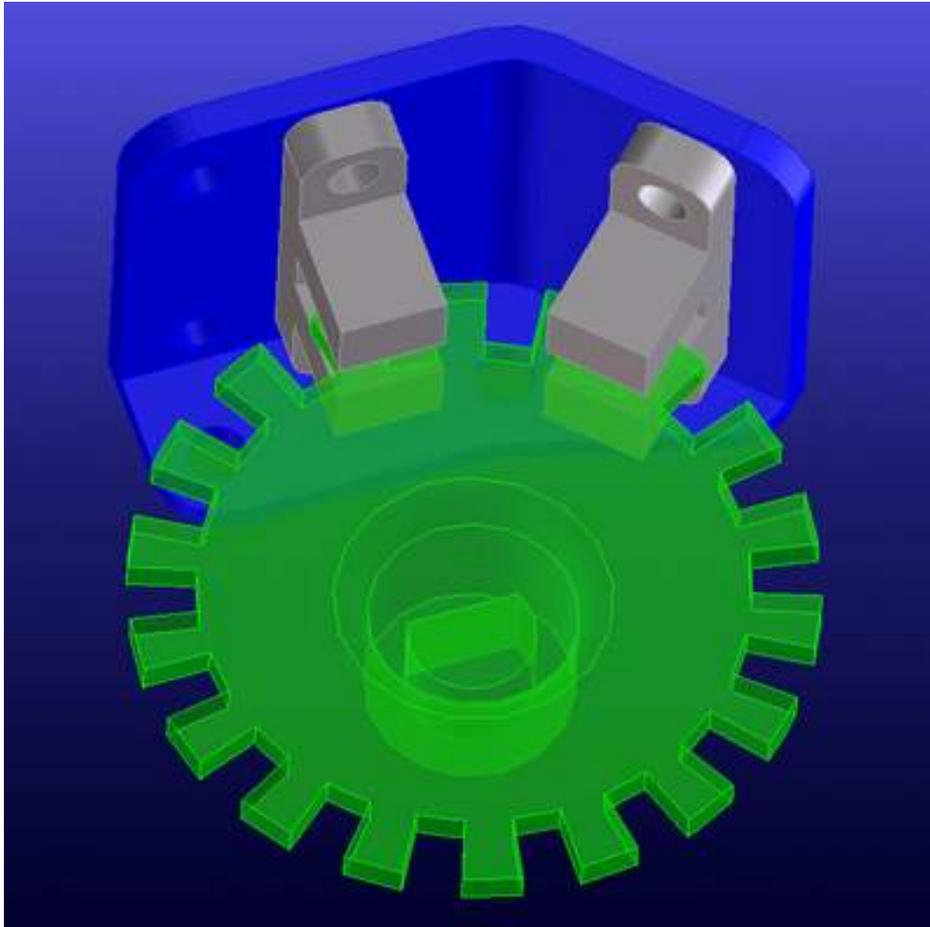
I think a second coat on the underside will improve it further. The waves are not in quadrature because somehow I managed to get the angle wrong, so I will have to make another bracket. It will function fine at half the resolution so I might press on with the extruder first.

So a cheap and cheerful shaft encoder, but not very high resolution. Since slotted optos are just LEDs and photo transistors in a bit of plastic, I think I will make another one with the raw components that will be even cheaper. I could put some more teeth on but that would make it harder for people to make and I want people to be able to upgrade their machine with their machine. Another way to do it is by printing onto film with a laser printer. There is a good site about that [here](#).

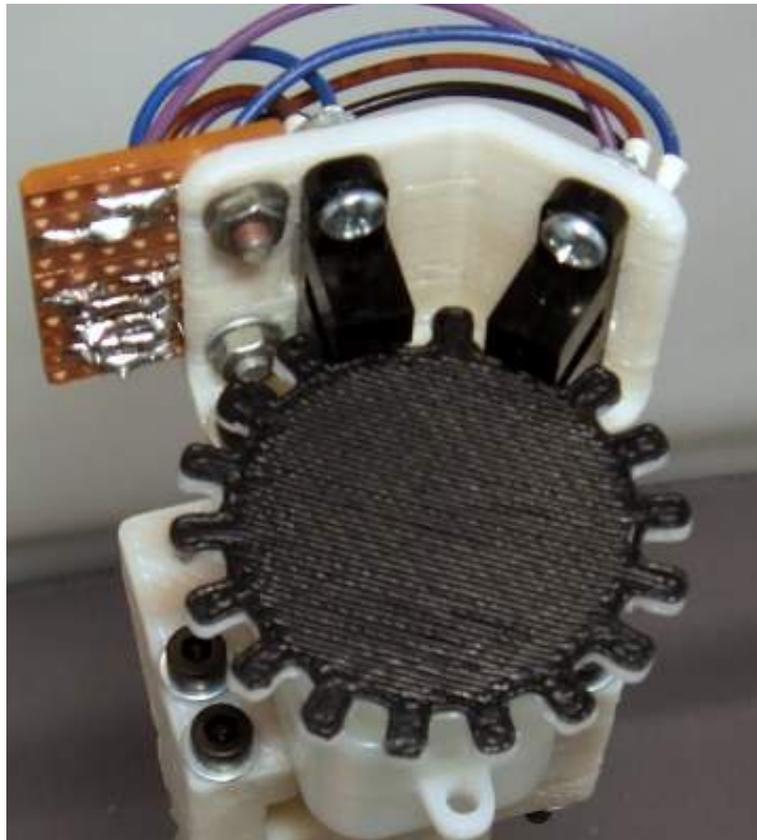
# Shaft encoder, second attempt

Friday, 22nd August 2008 by Nophead

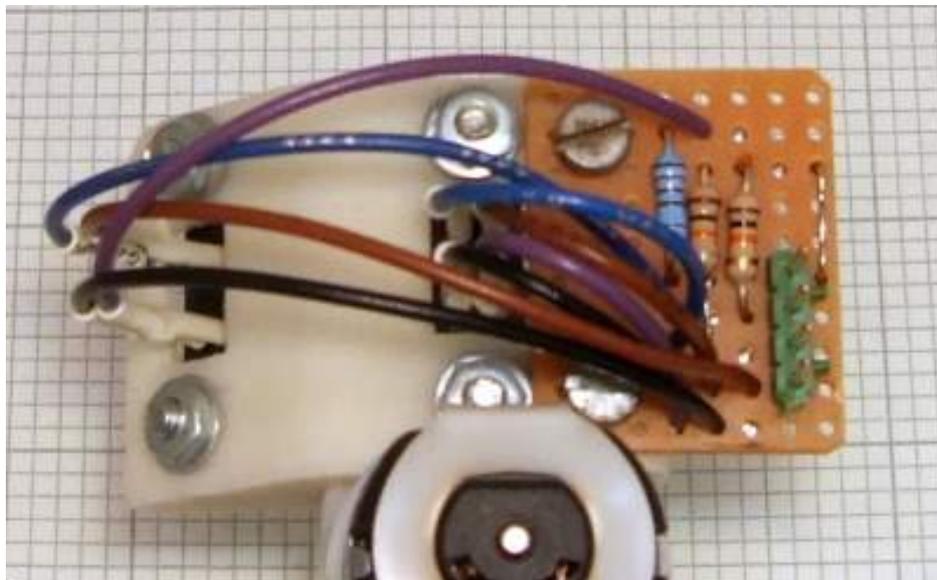
I made a right mess of the first design, not only did I get the angle wrong but the second opto is also at the wrong radial distance, which is why its amplitude was less. So I had to redesign the bracket, here is my second attempt: -



The correct angle for quadrature needs to be  $(K + 0.5)(180 / n)$  where  $n$  is the number of slots in the wheel and  $K$  is an arbitrary integer. The first convenient angle which straddles the bolt through the motor is  $45^\circ$ .

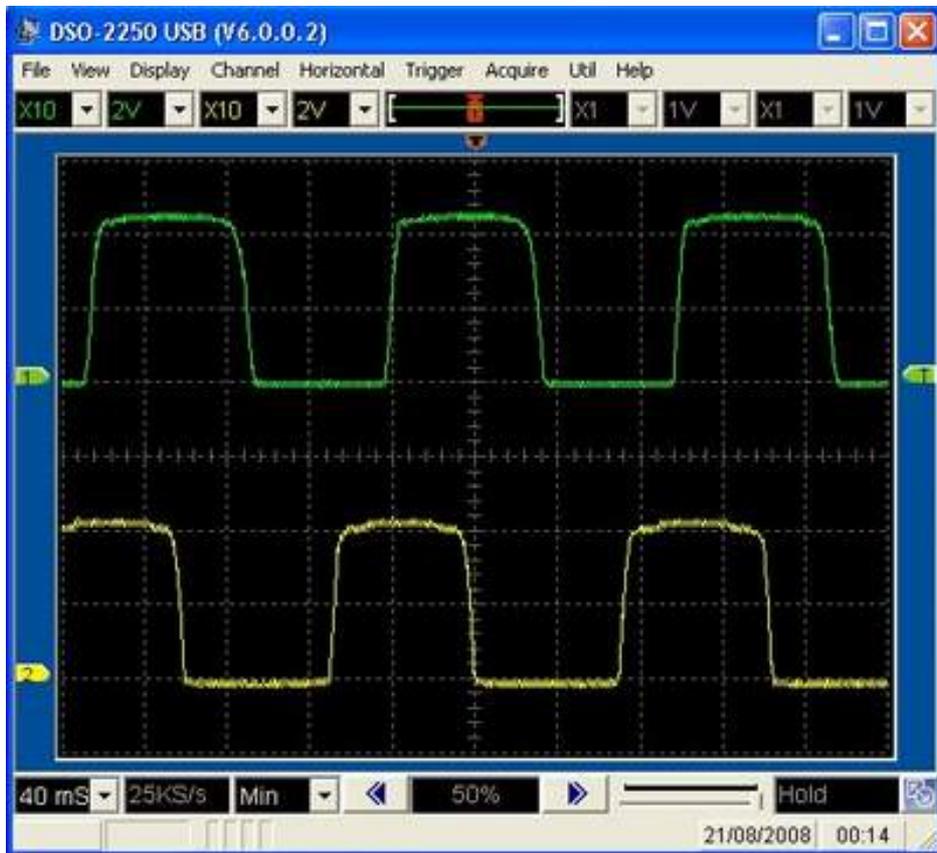


A single coat of BBQ paint seems adequate to block the IR beam.



A bit of a pain to wire up! If it proves to be a useful encoder I will design a pair of PCBs.

The waveforms are now both full amplitude and in quadrature: -

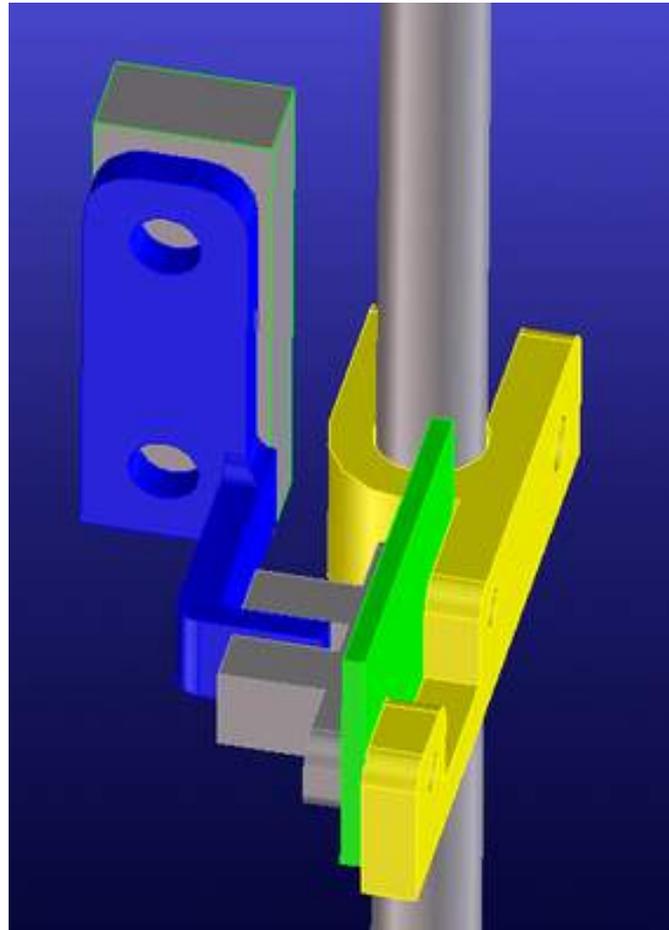


The edges are slow because I am using 4 pin optos, Zach seems to have bought up the world's supply of the five pin ones for the RRRF! The five pin versions have a built in Schmitt trigger to square up the waveform before it goes down the cable. Most micros have Schmitt trigger inputs these days but the disadvantage is that any noise in the cable will advance or delay the edge slightly, giving a timing error. Given the imprecise nature of this encoder I don't think it will make much difference.

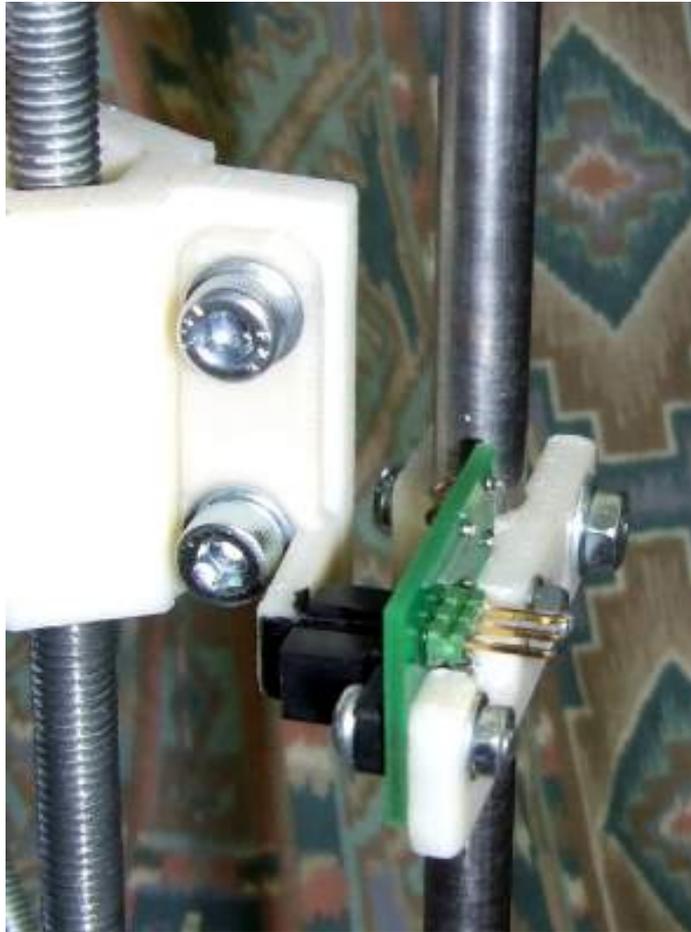
# Alternative Z-endstop

Sunday, 24th August 2008 by Nophead

I prefer my machine to home the z-axis away from the workpiece so that homing is always a safe operation, regardless of what state the machine is in. The standard endstop bracket allows the opto to be mounted on the horizontal rails but for a bottom endstop it needs to be mounted off one of the vertical posts. I designed a new bracket and tab for this: -



The tab enters the opto from the side which gives the best resolution. Here it is installed :-



It can be mounted anywhere on the vertical post so could be used as a top endstop as well but I don't see the point of stops at both ends.

The way I calibrate HydraRaptor's z-axis for FFF is that I get the head somewhere near the table and measure how far away it is with a rule to get rough calibration. I then instruct it to go to 3mm above the table. I roll a 3mm bright steel rod under the nozzle and jog the axis up and down in s/w until it just touches. This has to be done with the nozzle fully warmed up to the working temperature because the PTFE expands about 0.5mm.

The calibration drifts on HydraRaptor because the frame is made from wood so the weather affects it, something that Darwin should not suffer from.

The files are here: [www.thingiverse.com/thing:124](http://www.thingiverse.com/thing:124).

# Back to black

Monday, 25th August 2008 by Nophead

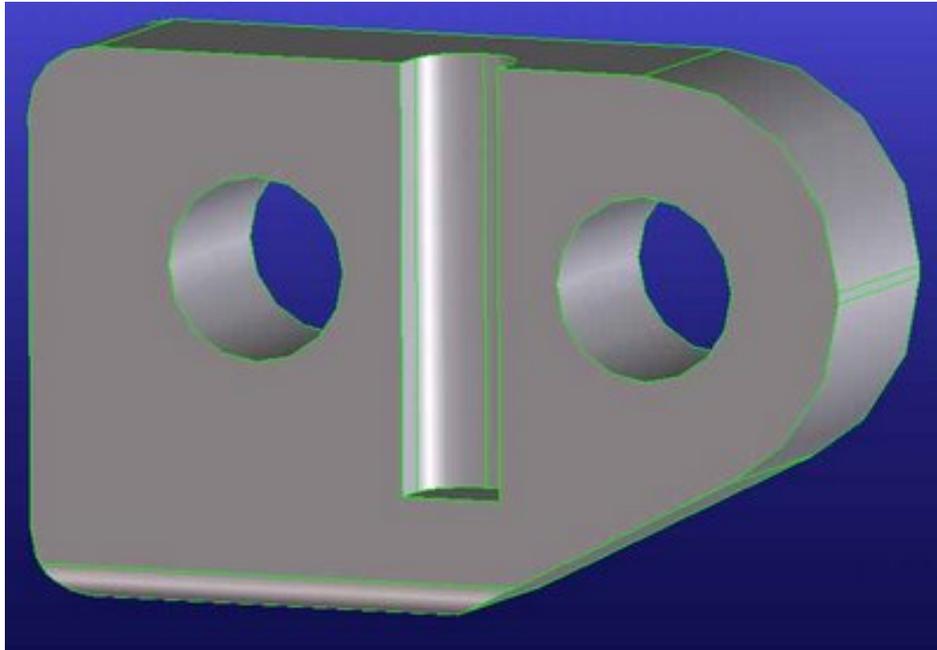
I have used up all of the 5lbs of ABS that I bought from the RRRF with just a couple of plastic parts left to make to complete my Darwin. I bought 2Kg of ABS from Tempatron but it is too oval to fit my current extruder, so it will have to wait until I build the new extruder for my Darwin. In order to complete that extruder I have had to go back to using HDPE. I always intended to make the filament guide for it out of HDPE anyway, because it is a lot more slippery than ABS, PCL and PLA.

It is quite a while since I did any work with HDPE and I didn't print many modeled objects with it before I switched to ABS, just lots of test blocks. In the meantime I have rebuilt and tweaked my extruder quite a lot and changed the way I do rafts. It took me a few attempts to dial in the parameters to get reasonable print quality.

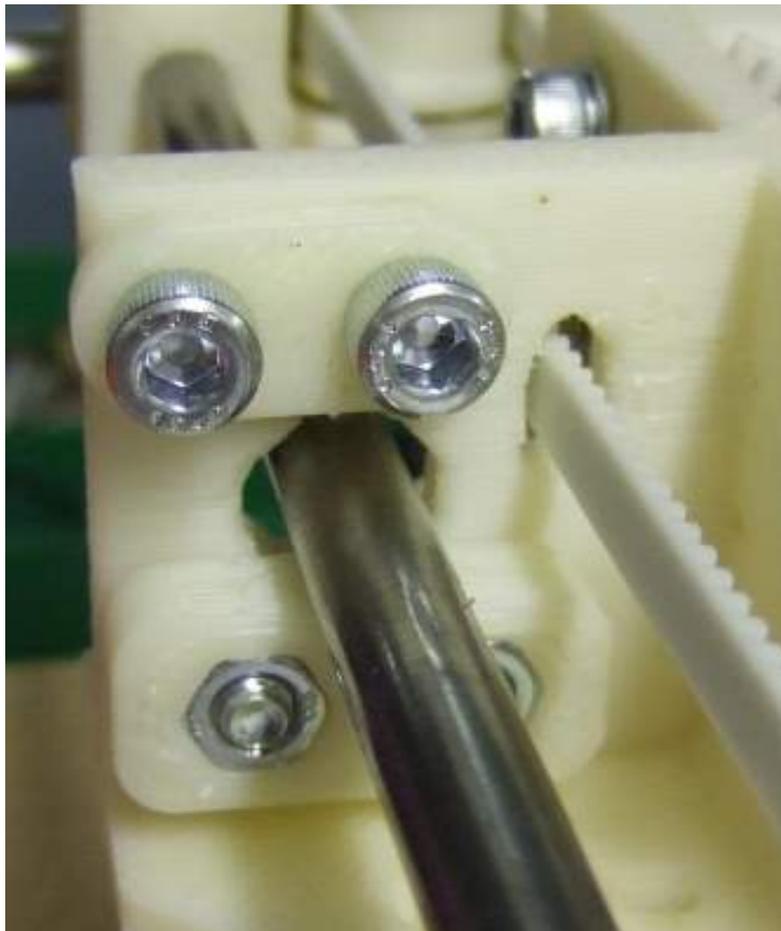


In the end the result is not bad. The object on the far right is an ABS version, the one next to it is the best HDPE version.

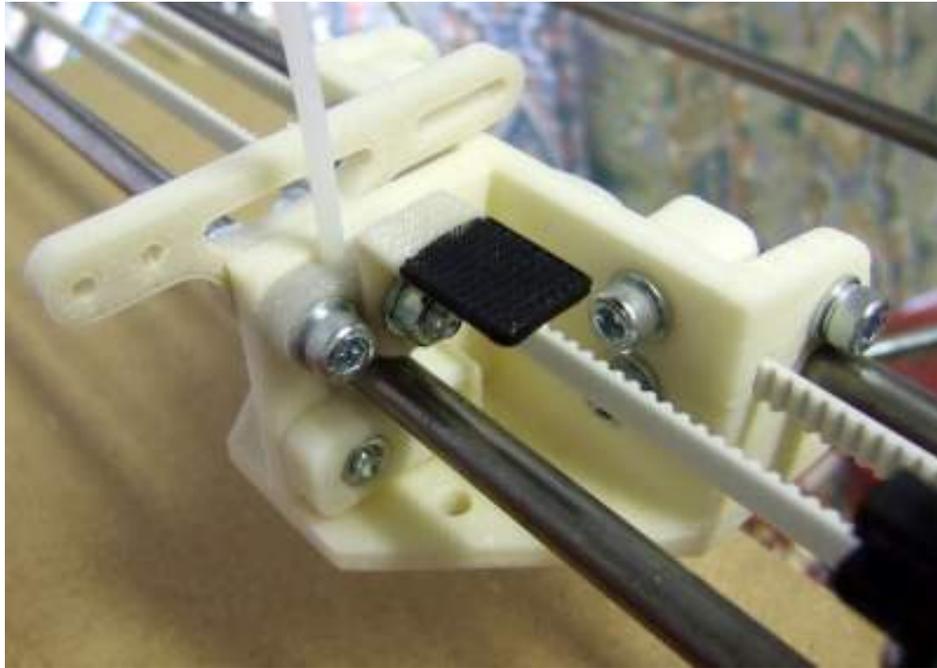
The test piece is an alternative solution to the problem Vik mentions here: [new-x-carriage-hot-off-reprap](#).



It replaces the y-belt clamp that holds a piece of filament (which carries the cables to the extruder) and also provides the bearing surface missing from the "no support" version of the Darwin x-carriage. You can see the gap above the bar created by the teardrop shaped hole below: -



Here is the new HDPE piece installed: -



It also fixes the fact that the screw hole pitch of the belt clamp does not match the holes in the carriage. HDPE is very good for making bearings so I intend to remake all the bearing inserts in it when the ABS ones wear out.

The first thing to do is get the raft temperature correct to make it stick, but still be peelable from the chopping board. I start with the temperature at a value I know will be too low and go up in steps of 10°C until it sticks enough, but not too much.

The next thing I do is get the first layer temperature right so that the object can be separated from the raft. I found that quite hard to control with ABS and much more so with HDPE. I increased the temperature until the outline started sticking properly and found a small test object was still peelable. When I made larger objects they were stuck fast. I normally use a small penknife to separate stubborn objects but after stabbing my fingers three times I resorted to a chisel! I think some of the variability is down to changes in ambient temperature and bed temperature. The XY table of HydraRaptor is made of several Kg of aluminium, which acts as a heatsink for the motors. They run a lot cooler than my Darwin's motors despite having more power through them. The table slowly warms up to about 30°C, about 10°C above ambient. 10°C is enough to make all the difference between sticking and not. I probably need to measure raft surface temperature and adjust the first layer accordingly. Another thing to try would be to do the first layer outline hotter than the infill.

I dropped the build speed from 16mm/s to 8mm/s for three reasons: -

- HDPE puts maximum strain on the extruder because it is the most viscous at extrusion temperature so it is both the hottest and the highest pressure.
- Heat builds up in the object limiting the minimum size that can be made without inter-layer pauses, something I have not implemented yet.
- HDPE likes to cut corners and not go where it should and I think going slower helps the

accuracy.

I also had to set the infill overlay parameter to 0.5 in Enrique's software to make the infill join to the outlines correctly.

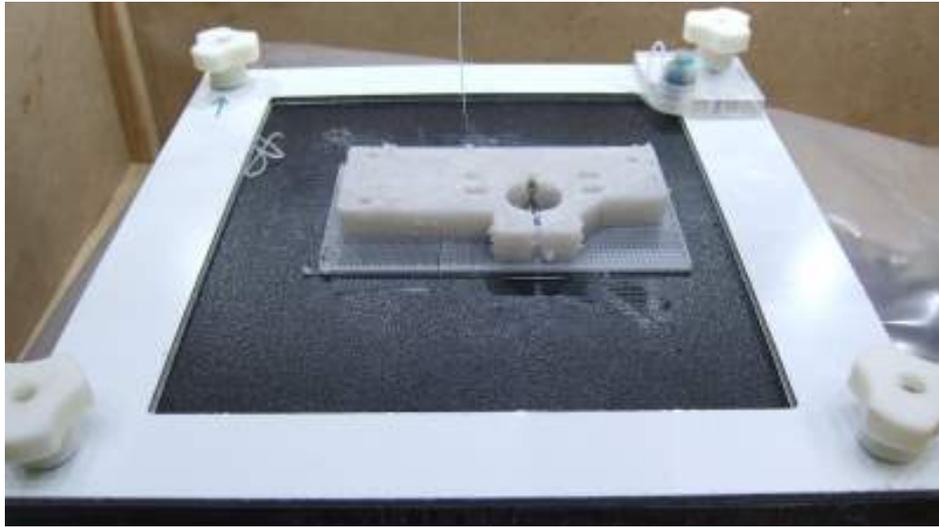
A few things that are different about HDPE:

- Extruder ooze creates blobs rather than strings with my current nozzle. They are harder to remove because they are a lot thicker. Faster head movement on my Darwin should drastically reduce this effect.
- The brush I use to wipe the nozzle works perfectly with HDPE but not very well with other plastics. This is because HDPE extrudes in a straight line and is not very sticky. In contrast ABS tends to curl upwards and sticks well to the nozzle.
- HDPE spans gaps a lot tighter than ABS does because when it is stretched it remains under tension whereas ABS doesn't.

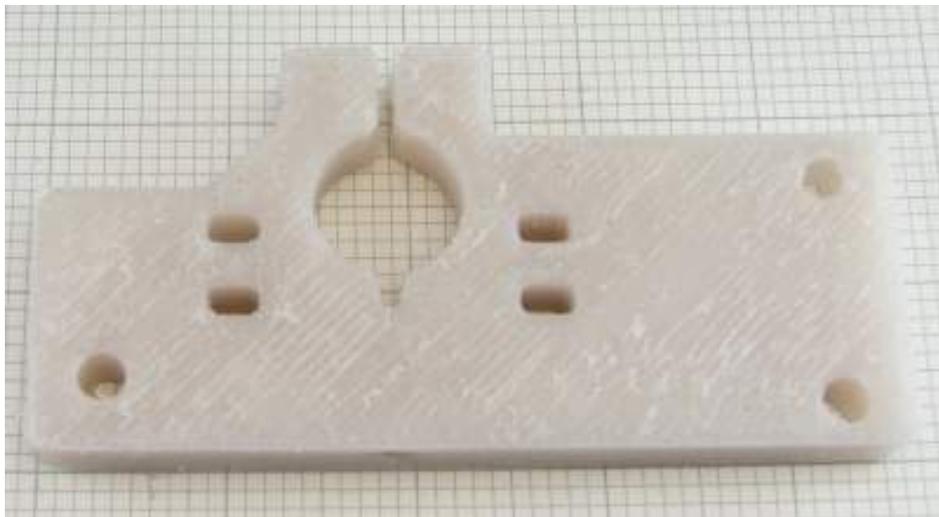


- Holes always come out smaller than they should be, but with HDPE this effect is worse. Dr Bowyer published a correction formula based on there being too much material on the inside of circles but I get contractions an order of magnitude greater. I think it is related to how much I stretch the filament but I need to do some more work on it.

I then made the extruder clamp in HDPE. It is a bit warped of course but it doesn't really matter. The raft was strained upwards at the bottom left corner, not surprising as this is one of the longest pieces I have made.

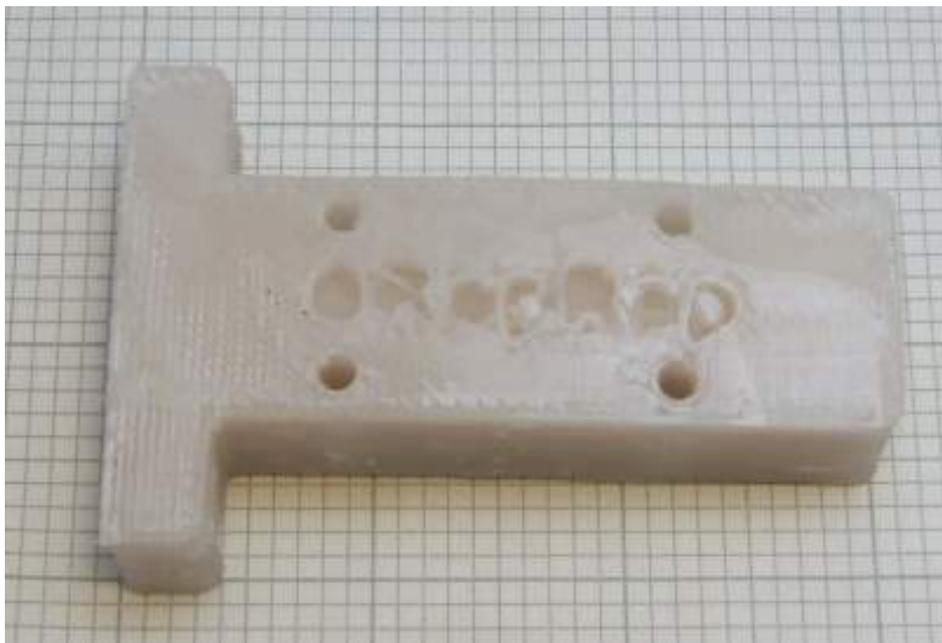
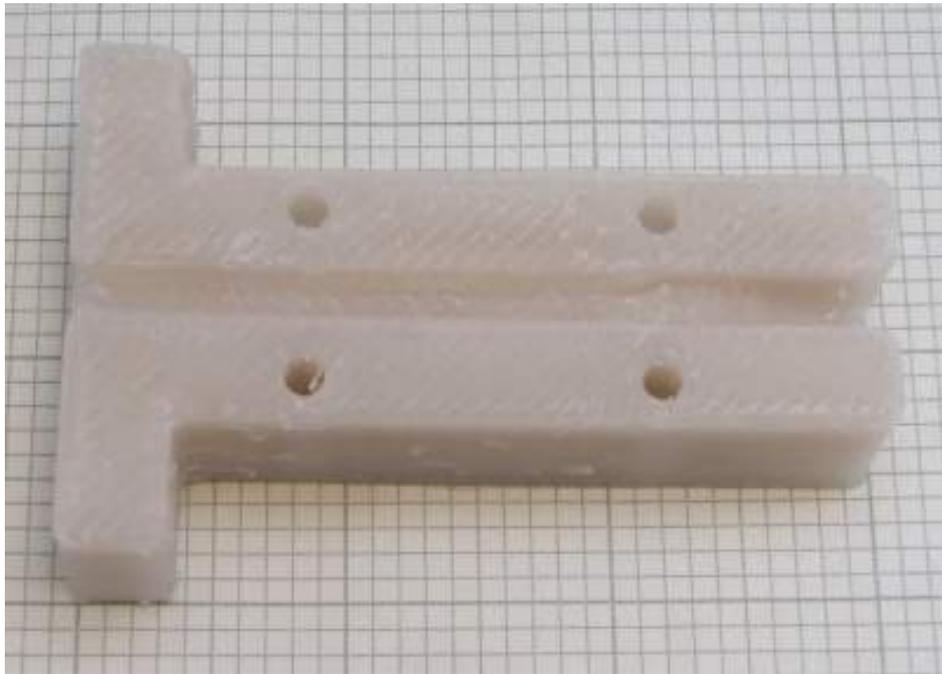
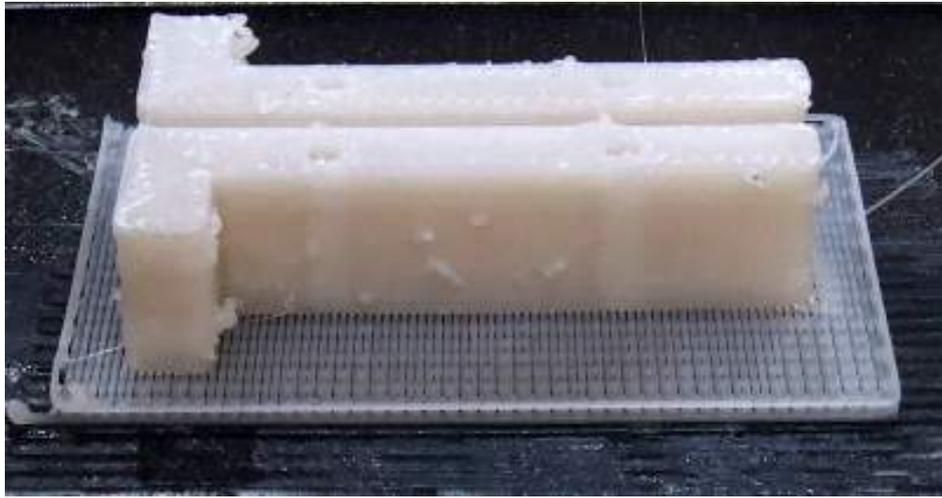


Here it is cleaned up :-



The large hole for the PTFE barrel is undersized and my PTFE stock is oversized so I think I will have to turn it down to get it to fit. I drilled out the other holes.

Similarly the filament guide is warped on the underside but it is only the top side that needs to be flat.



As predicted it is slippery and my oval ABS glides through it very well.

I just have to make the metal extruder parts now and that completes the mechanical build of my Darwin.

# Bearing fruit

Tuesday, 26th August 2008 by Nophead

My wife has been asking me to make something to prop up the overladen branches of our dwarf apple tree for a few weeks now. I put it off while I was set up for ABS because I knew I did not have enough to finish my Darwin. Now that I have switched the machine to HDPE it is no problem, but it is now a few days late as one large branch has already snapped off!

We have lots of plastic covered metal poles so all I needed to do was make some Y-shaped end pieces. My first attempt went a bit chaotic while making the arms: -



I wasn't watching it but I figured it got too hot when doing the small pieces so I made the arms thicker.



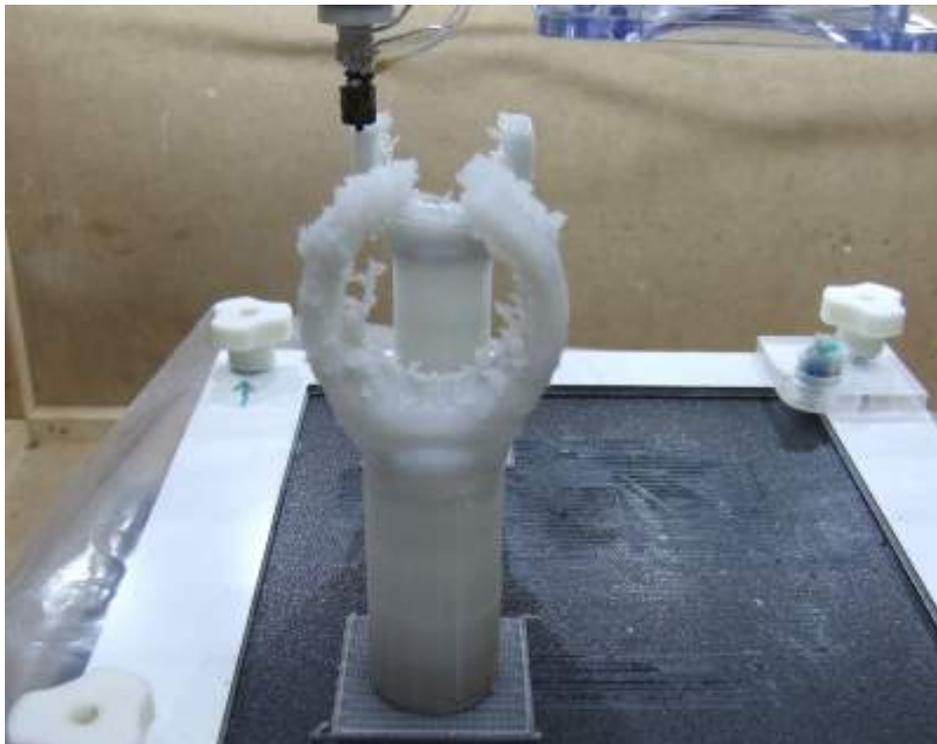
Better but still very rough, it should look like this :-



I cleaned it up with a penknife and it was functional but it felt more whittled than extruded.



I made a couple more with even thicker arms but I was around to observe what was going wrong this time: -



When building the curved arms Enrique's software switches to 100% fill because it decides part of the layer is two layers from an outer horizontal surface, which a thin sliver down each side is. That would not be a problem in itself but because I have the infill overlap option set it ends up with slightly too much plastic on the 100% layers. As the height increases this excess builds up until the nozzle is actually submerged in the object while it is building it. Amazing that it manages to make anything resembling the correct shape!

What really needs to happen is that if the infill overlap parameter is set then the head needs to lay down the infill slightly faster so that the amount of plastic is still correct. I ran into the same problem with ABS when making an object with 100% fill.

I made a fourth version with the infill overlap set to zero and it was a lot better: -



Still very blobby but all the blobs are down to extruder overrun and easier to carve off. Overrun is worse with HDPE because it seems to be a more non Newtonian liquid than ABS. I.e. it compresses and expands more than ABS does, so when the extruder stops it oozes for longer.

I haven't tried anything to stop ooze yet. Simply stopping the extruder before the end of the line like the RepRap host does should improve it and is easy to do. Reversing the motor drive should also help. Simply stopping causes the extruder flow rate to fall exponentially but backing up a little should stop it completely in a finite time. The shaft encoder can then be used to go back at full speed to where it was before it backed up. There will still be some ooze without a valve but I think it could be a lot better.

Here is the final version cleaned up: -



And here is the tree with four crutches installed although only three are visible from this view though: -



# Screw Top Pot

Monday, 1st September 2008 by Nophead

A day before going on holiday I decided I needed a container to store the lens adapter for my camera. The lenses have caps on each end, but they require an adaptor which is a bit delicate: -



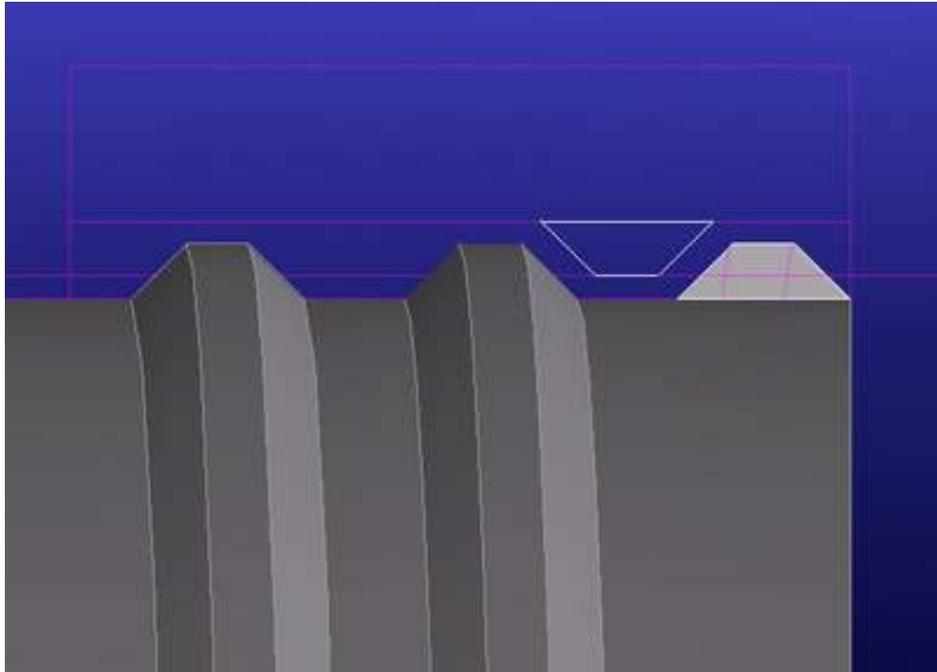
I knocked up an HDPE pot with a screw top lid that just the right size to hold it: -



The outside diameter of the adapter is about 48.5mm so I made the pot I.D. 50mm to allow some clearance. It actually shrank to 48.5mm, so it is a snug fit. Lucky it didn't shrink any more!



I made the thread using the helix tool in CoCreate. You draw a 2D profile and then use the helix tool to spin that round an axis, specifying the pitch. The dimensions were just a stab in the dark: I made the crest of the thread 0.8mm as that is two layers (Nyquist sampling theorem) and made the sides 1mm long 45° slopes, so that made the crest height 0.7mm. The minimum pitch with this profile would be about 3mm so I made it 3.5mm to give some clearance. I also made the the lid 1mm bigger radius so there is 0.3mm clearance from peak to corresponding valley.



A couple of things I missed which would make it easier to engage: -

1. The thread starts abruptly, but it should have a tapered lead in.
2. Both the pot and the lid should have a few millimetres with no thread to aid lining them up before the thread engages.

Despite this it works surprisingly well for a first attempt with an arbitrary profile and dimensions.



I am slowly homing in on getting rafts peel-able for HDPE. I made this with the first layer outline hotter than its infill :-

HDPE.raft\_temp = 215

HDPE.first\_outline\_temp = 230

HDPE.first\_layer\_temp = 205

HDPE.layer\_temp = 240

Most of it peeled with a little encouragement from a chisel at one side.

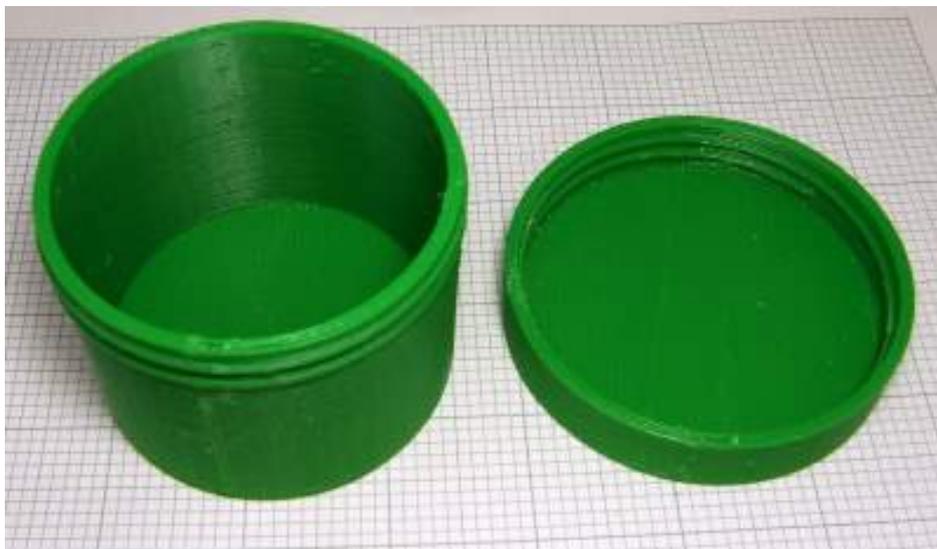
# Going green

Monday, 22nd September 2008 by Nophead

Getting a bit bored of natural ABS, which is cream coloured, I ordered some black and some green from New Image Plastics in the USA. Despite the high cost of shipping it still worked out cheaper than buying it in the UK. I chose green because it should be easier to photograph than black or white and it the RepRap logo colour.

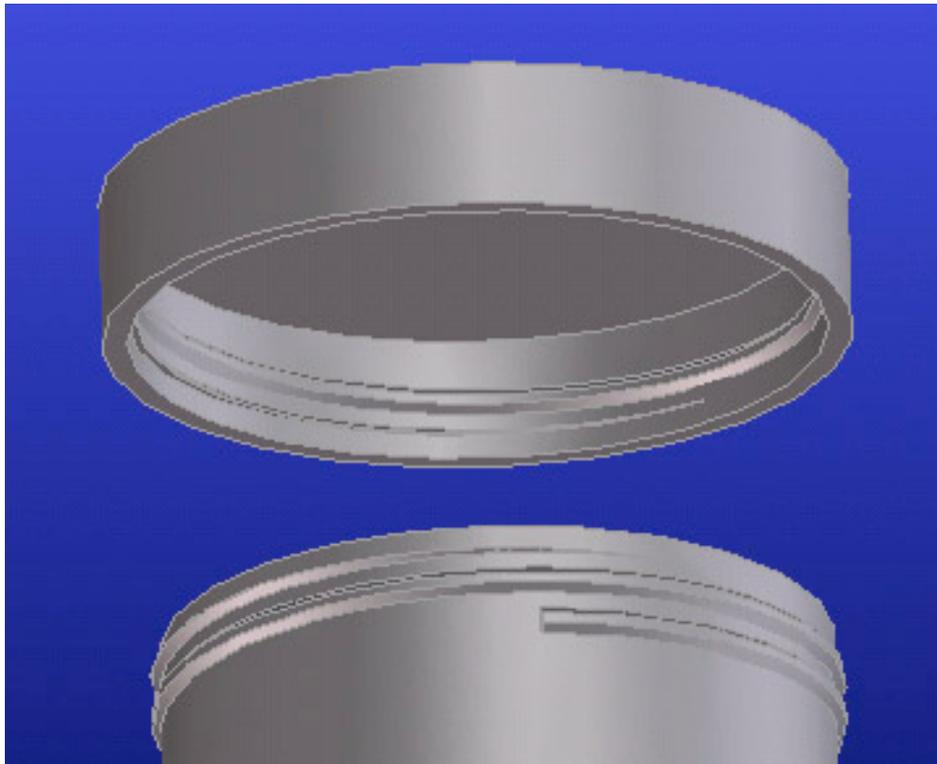
I was surprised to find that it does not behave the same as the natural that I got from the RRRF. It does not seem to stick to itself, or to the base material, as well as the RRRF ABS did at the same temperature. I have raised all the temperatures by 15°C and, although it is better, I think it still needs bit more. It's appearance is more glossy, so that might account for it being less sticky, or it may just have a slightly higher melting point. I have no idea if the green dye has an effect or whether the base ABS is different. It will be interesting to try the black.

I made a new version of my screw top pot in order to perfect the thread before posting the STL files on the RepRap Objects wiki. It turned out to be nightmare to get it to print. Besides the problem of it not sticking to the bed, my extruder kept breaking GM3 gearmotors, but that's another story.



The ABS version came out about 1mm bigger in diameter than the HDPE version due to lower shrinkage.

I modified the thread to make it easier to start. The original thread started abruptly at the top of the pot and the bottom of the lid. I modified it in CoCreate by continuing the helix past the top of the pot and then milling it back to 2mm below the rim. I did the same to the lid's thread. That allows the lid to overlap 4mm before the threads engage, making it easier to line up. The thread now tapers out to a thin sliver to make it easy to engage. The result works a lot better than the previous attempt.



# Spurred into action

Friday, 3rd October 2008 by Nophead

Forrest's success at milling spur gears with Tommelise 2.0 got me wondering how well RepRap can make them with Fused Filament Fabrication. An obvious test case are the two gears on Ian Adkins' alternative extruder design. These are laser cut, but look just about achievable with FFF. I couldn't find a picture of Ian's, these are a similar design by Vik Olliver.



Here is how they came out :-



The infill does not meet the toothed edge very well but they seem very strong never the less. They mesh well even though the involute profile seems a bit rounded off.

In an attempt to get the infill to work better I tried running my machine with 0.3mm filament, 0.24mm layers. I didn't make the nozzle hole smaller, I just changed one number in my software so the filament is being stretched finer. The result was interesting :-



The infill fills the teeth and is also very flat. The hole for the motor shaft has come out smaller and the teeth are a bit asymmetrical. They lean clockwise, the direction the outline is laid down in. I think this is because I am extruding 0.3mm filament through a 0.5mm hole so the point it exits from can move about but 0.2mm. I expect using a 0.3mm hole will solve that.

I also had a go at making a smaller version of my screw top pot with 0.3mm filament. I used the same g-code, I just scaled all the coordinates by 0.3/0.5.



It came out well and the thread still works.

With the finer filament it takes about 3 times longer to make anything so I upped the speed from 16mm/s to 32mm/s. That had an unfortunate side effect: The wall of the pot is quite thin so after the outline and inner wall have been extruded, the infill is a very narrow zig-zag. That makes it a high frequency movement. Speeding it up made it more like an audio vibration which seems to resonate the frame of my machine, shaking anything loose off the desk.

[HydraRaptor growling](#) from [Nop Head](#) on [Vimeo](#).

# Brain dump

Saturday, 4th October 2008 by Nophead

I have added a page to the new Reprap Builder's wiki recording all I know about the original MK2 extruder. I make no apologies for including lots of links back to this blog and recycling some photos, but there are also many new ones.

Although the design has moved on, I have stuck with the original and tweaked it to fix the problems I have encountered. I don't think any of the later, more complex designs have better performance, except perhaps the anti-ooze version. That seemed like a nice idea but rapidly got too complex with a double nozzle and two heaters plus some tricky machining. I think instead stringing can be mitigated to a large extent by increasing the speed of moves between extrusions paths. I am hoping to go from 32mm/s on HydraRaptor to 150mm/s on Darwin. Also I think reversing the extruder motor a fixed amount measured by the shaft encoder, plus Enrique's oozebane and comb modules in Skeinforge should help a lot.

# Brassed off

Monday, 6th October 2008 by Nophead

My first attempt at an extruder had stainless steel bearings and a stainless steel drive shaft, more by accident than anything else. I wondered at the time how the bearings would last compared to the recommended brass ones. Obviously stainless steel is harder than brass, but brass should have less friction, so less wear.

The first drive shaft got retired because the bearing lands were off centre. At the end of its life the bearings and lands were still in good condition.



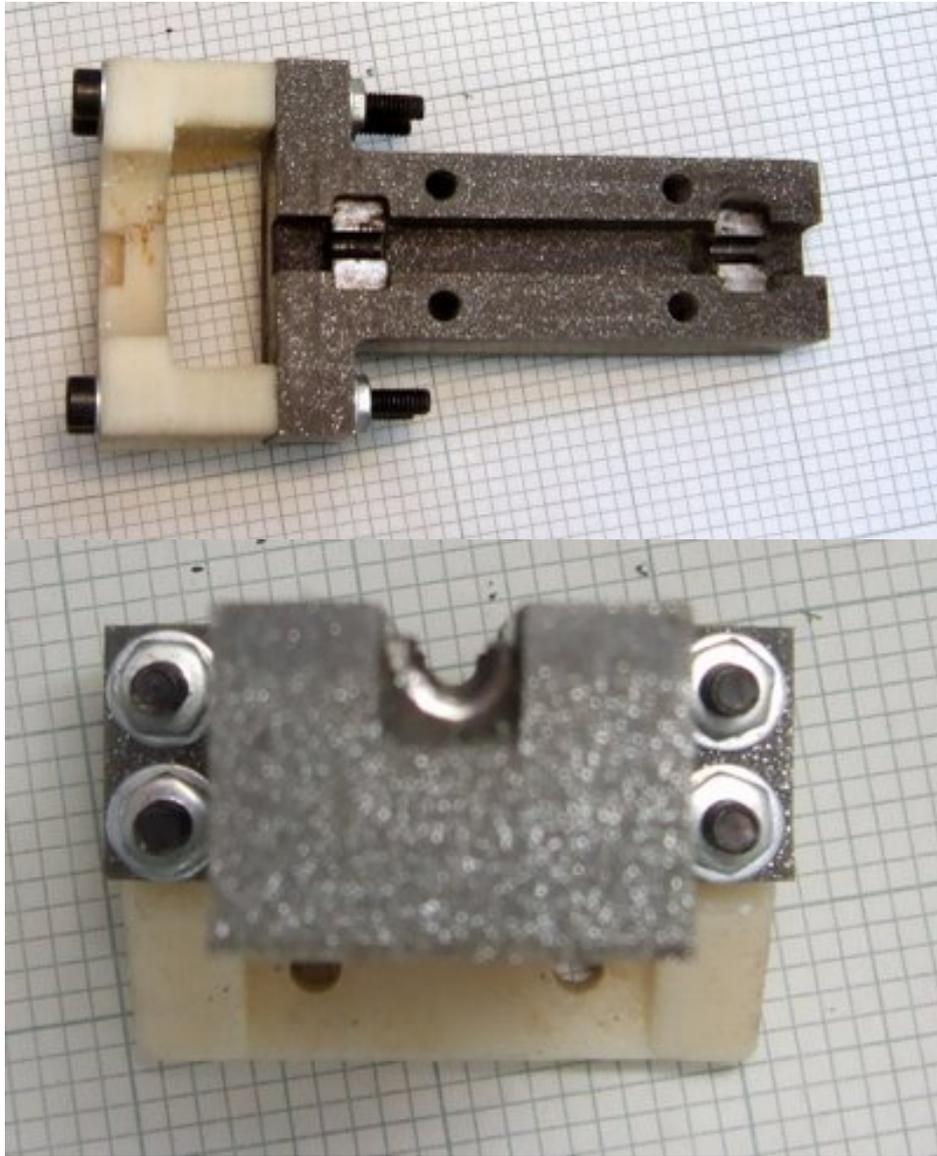
I ran it from 10/07 to 01/08 but up to that point all I had made was lots of HDPE test shapes.

I replaced it with a plain steel shaft that I bought from BitFromBytes. That had the big advantage of being solder-able.

It worked well for a long time but eventually the bottom land on the shaft wore down so much that the pump halves closed together when using undersized filament (2.7mm).



The bottom land has worn down from 3mm to 2mm. The bearings show a little wear but still have some life left in them. This is after running 5lbs of ABS through the extruder.



In the last few weeks I replaced the shaft with a new zinc steel one and switched to brass bearings in an ABS extruder with HDPE filament guide. That worked well until I noticed the pump halves closed together again. When I opened it up I found that the brass bearings had rotated in the ABS, but they had also worn down a lot, considering the short time I had used them.



The drive shaft lands are still fine though.



So it would appear that the best combination is stainless steel bearings and a stainless steel shaft, but I would have to find another way of attaching the nut.

Most metal bearings I have recovered from old equipment are bronze. I don't know how that compares to brass but it seems to be the thing to use.

Maybe it is time to look at ball bearings and an offset shaft like Ian Adkins' design.

# Pot black

Thursday, 9th October 2008 by Nophead

Having tried green ABS and found it a bit disappointing, I had a go with black ABS and was even more disappointed. I got it to try and make objects a bit more aesthetically pleasing but it was even harder to get working than green and has aesthetic problems as well.

The temperatures seem to be the same as those for green, i.e. higher than I have used for plain, but it is harder to get it to stick to the raft and it de-laminates more readily.

To make it stick I had to make the first layer a bit lower than normal. With plain ABS I can have it at the normal layer height above the raft (filament diameter \* 0.8) but with HDPE and green ABS I had dropped it 0.1mm. With black I had to drop it 0.15mm as 0.1mm does not stick enough and 0.2mm sticks too much. 0.05mm makes all the difference and has about the same effect as changing the temperature by 10°C.

Another problem is that the extruded filament is not smooth. Close examination reveals that it has small craters in the surface where it has out gassed. It is particularly noticeable when laying the thick filament for the first layer of the raft.



It could be the effect of water absorption but, as all my ABS is stored in the same room, I think it is more likely a volatile component of the black dye. Another effect is that if the filament is stretched while molten, so that it is drawn into a fine thread, then it looks like a string of beads. I think that is an indication the black dye does not mix well with the ABS.

Fortunately, for some reason I don't understand the crater effect is less noticeable when making objects.



These are Darwin y-belt-clamps, a nice small part good for a quick test. The small one is made with 0.3mm filament and shrunk by 3/5. As you can see it is far less shiny. All I can think is that is related to the fact the filament is being stretched more.

Another downside of coloured ABS is that ABS turns white if it is stressed. This shows up far more when it is coloured and particularly with black. Because the base of the object is weakly welded to the raft then it gets bruised when it is peeled off.

This is the bottom of another screw topped pot.

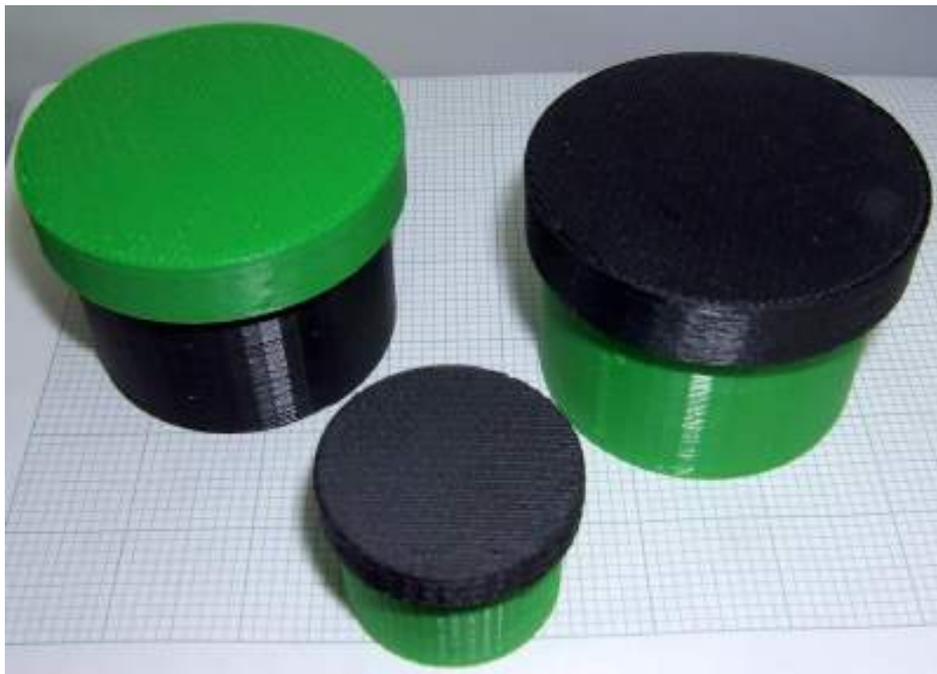


As you can see it has white highlights where the welds to the raft have been broken. One way of fixing it is to wave a hot air gun over it to relax the stress points. That also flattened the base, which was a little convex due to warping.



I expect rubbing it with a little solvent like MEK would also solve the problem.

I now have a little family of pots!



I would not recommend coloured ABS as the dye introduces more variables and generally seems detrimental to strength and aesthetics.

# New Toy

Tuesday, 11th November 2008 by Nophead

The company that I have worked at for 25 years gave me a long service award recently. I could choose anything worth £500 so I chose this small lathe / drill / milling machine combo. The tiny watchmaker's lathe I have been using up to now is not really big enough for RepRap parts. This should be just about right.



A combo like this is a bit of a compromise and only recommended if, like me, you have limited space. It gives me a lathe, pillar drill and milling machine in a small footprint.

I also bought accessories with my own money, which came to about another £300 :-

- Cutting tools - essential.
- Compound cross slide - for cutting tapers.
- Drill vice - to hold things on the cross slide when milling or drilling.
- Tailstock chuck - to drill down the axis of round things.
- 4 Jaw chuck - for turning square and irregular shapes.
- Milling chuck and collet set - to hold milling bits.
- Wiggler - for finding centres and edges when milling and drilling.
- Die holder - for tapping threads.
- Headstock centre - for turning between centres.

I have also made a couple of accessories with HydraRaptor. The first is very simple: a t-slot cleaner for removing swarf from the cross slide's t-slots.



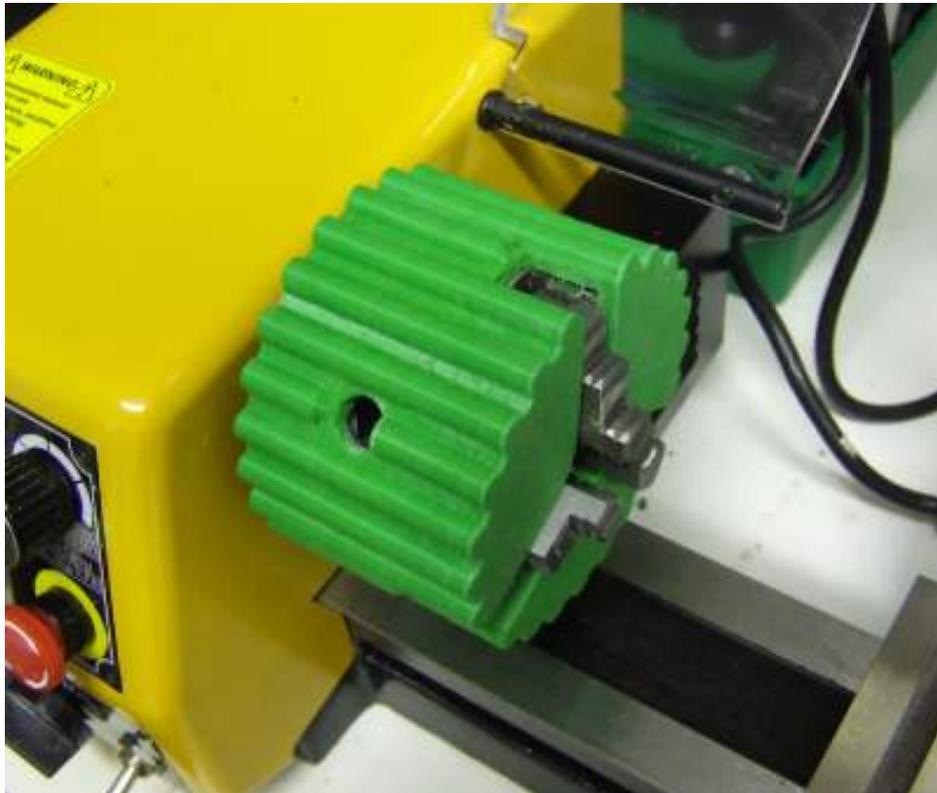
That saved me about £2.80.

The second object is the biggest thing I have RepRapped so far. It is a cover to go over the chuck to make it easier to turn by hand when tapping. It took over 7 hours to build and weighs 77g.





Here it is installed :-



I haven't used it yet but it feels like it should work well.

# Key Things

Monday, 17th November 2008 by Nophead

Zach Smith and Bre Pettis have created a web site called [Thingiverse](#), which is designed to make it easy for people to share digital designs of real objects. I have put most of the things I have designed for printing on a RepRap on there. I even created one especially for it, a key for reading utility meters :-





You can get these free from the utility companies, but not as quickly as you can RepRap one for a few pennies worth of plastic, and they are easily lost. The files can be found here :- [www.thingiverse.com/thing:88](http://www.thingiverse.com/thing:88).

I also keep a gallery of all the things I have made with HydraRaptor here: [sites.google.com/site/nophead/Home/hydraraptor/ThingsMade](http://sites.google.com/site/nophead/Home/hydraraptor/ThingsMade). They all now have links back to Thingiverse for the files.

A lot of the objects on Thingiverse are for a laser cutter, but I downloaded this twisted star box designed by Marius Kintel and printed it.

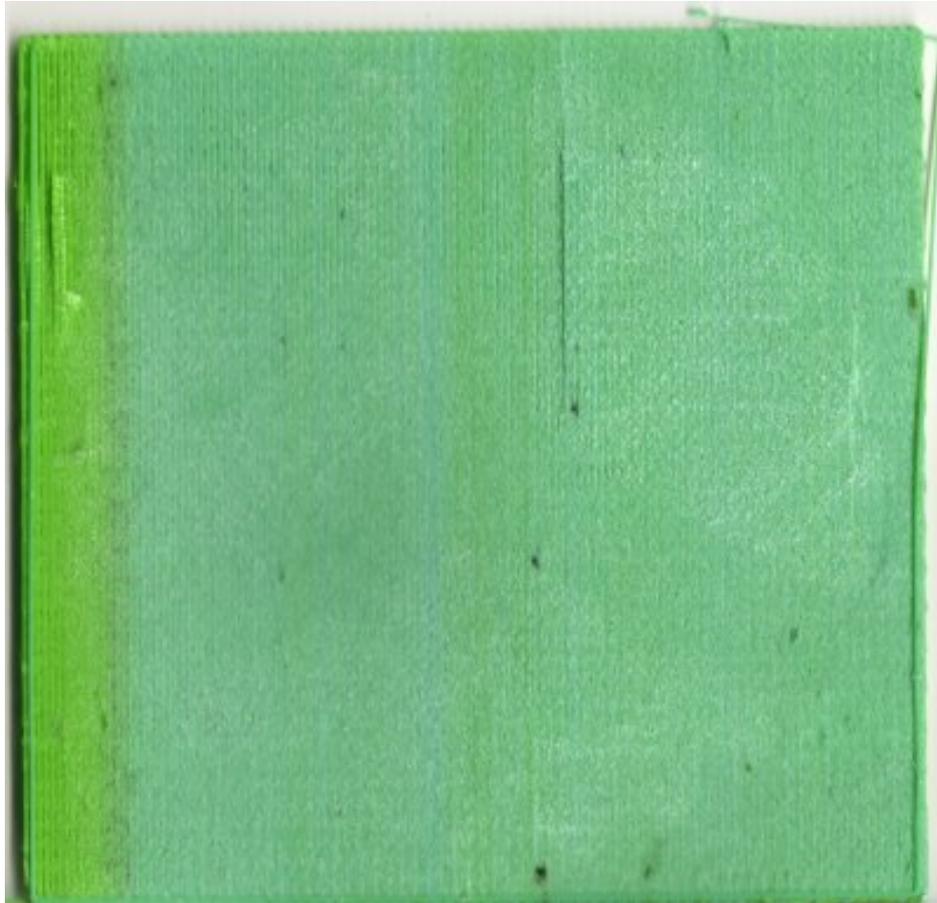


One trick I have learnt is that you can shrink objects a little by heating them with a hot air gun. When I first made this the top was too tight, so I shrank the bottom a little with the heat gun. It is now a perfect fit. You have to be careful not to get it too hot, or it will sag.

# Hot Stuff

Thursday, 20th November 2008 by Nophead

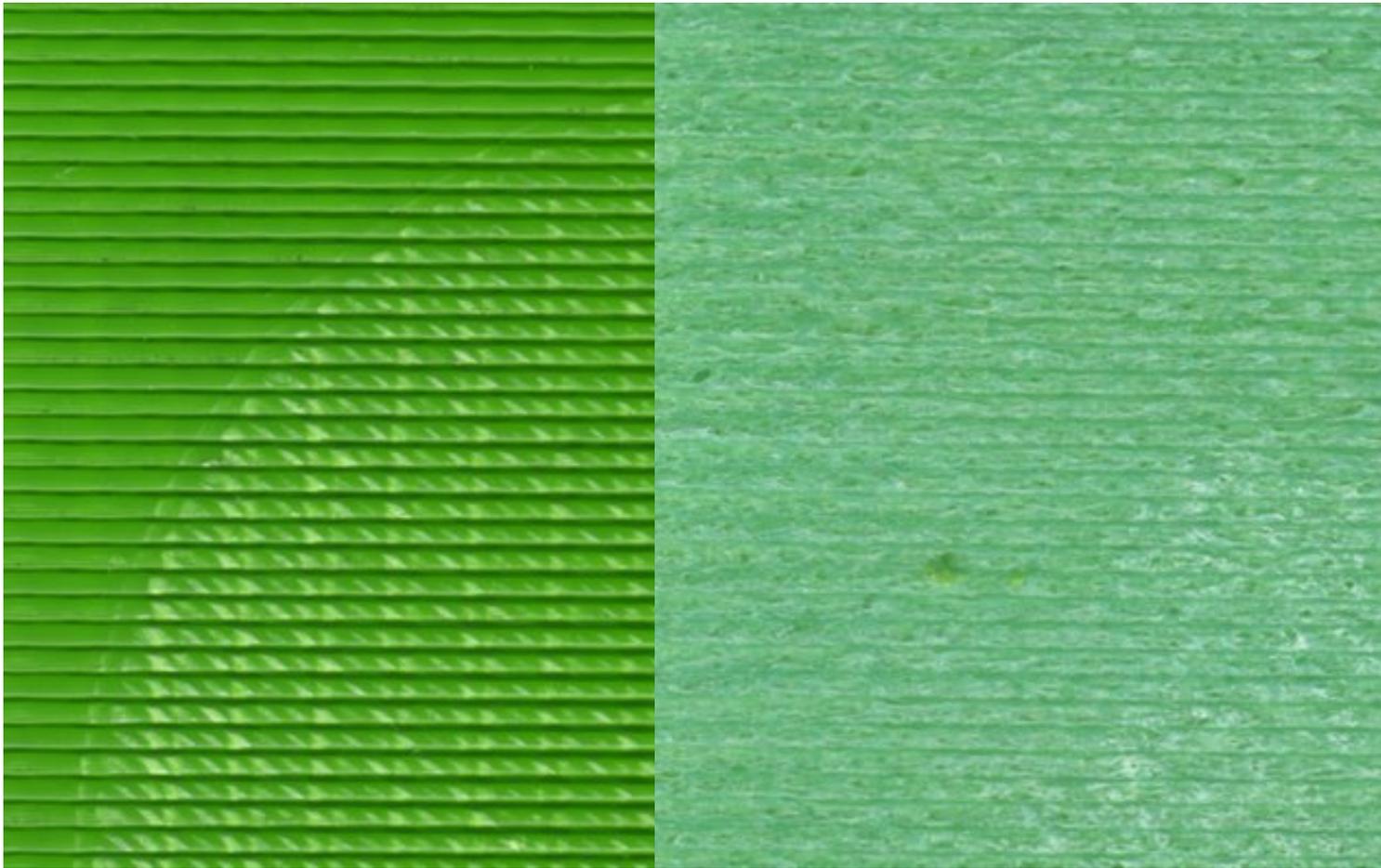
When I was making the chuck grip I noticed that the raft changed colour part way across the top layer of the raft.



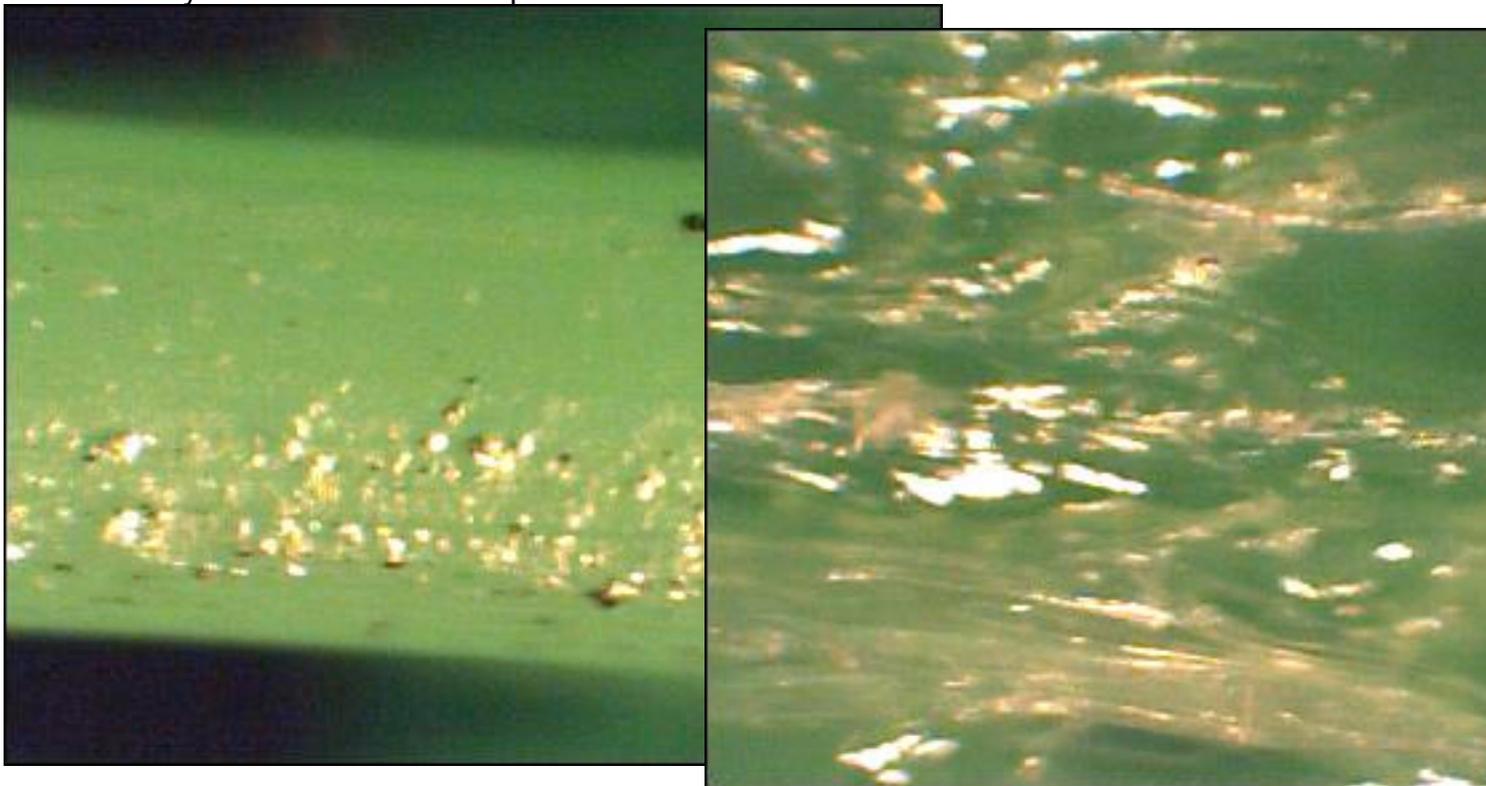
The heater seemed to be on 100%, so it looked like the plastic was way too hot. By the time I noticed it seemed to have reached thermal equilibrium and apart from some snap crackle and pop sounds, and a bit of smoke the extruder seemed happy. I was reluctant to abort the build because it had taken about an hour to get this far.

When it finished the raft it cooled down to the right temperature and built the object. The surface of the raft has a completely different texture and it seemed easier than usual to peel off the object. Despite that, it managed to hold down what was a very big object. The shape of the object was less prone to curling than most, being a large circle (no corners to curl up) split into three segments and with a corrugated outside perimeter, which could absorb shrinkage. I need to do more experiments to know if it is beneficial to deliberately make a raft like this.

This is what the normal and hot rafts look like close up :-



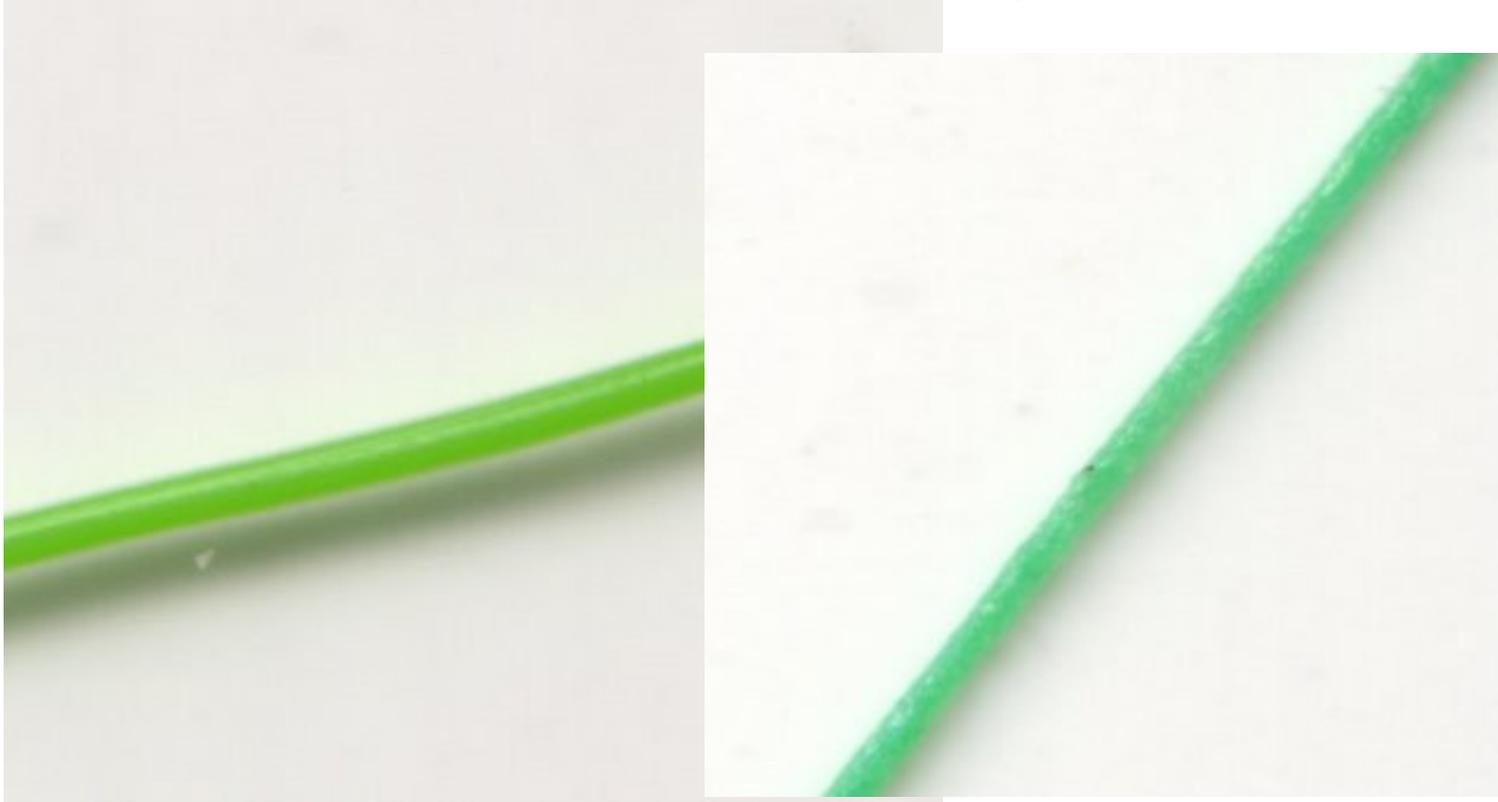
And here they are under a microscope :-



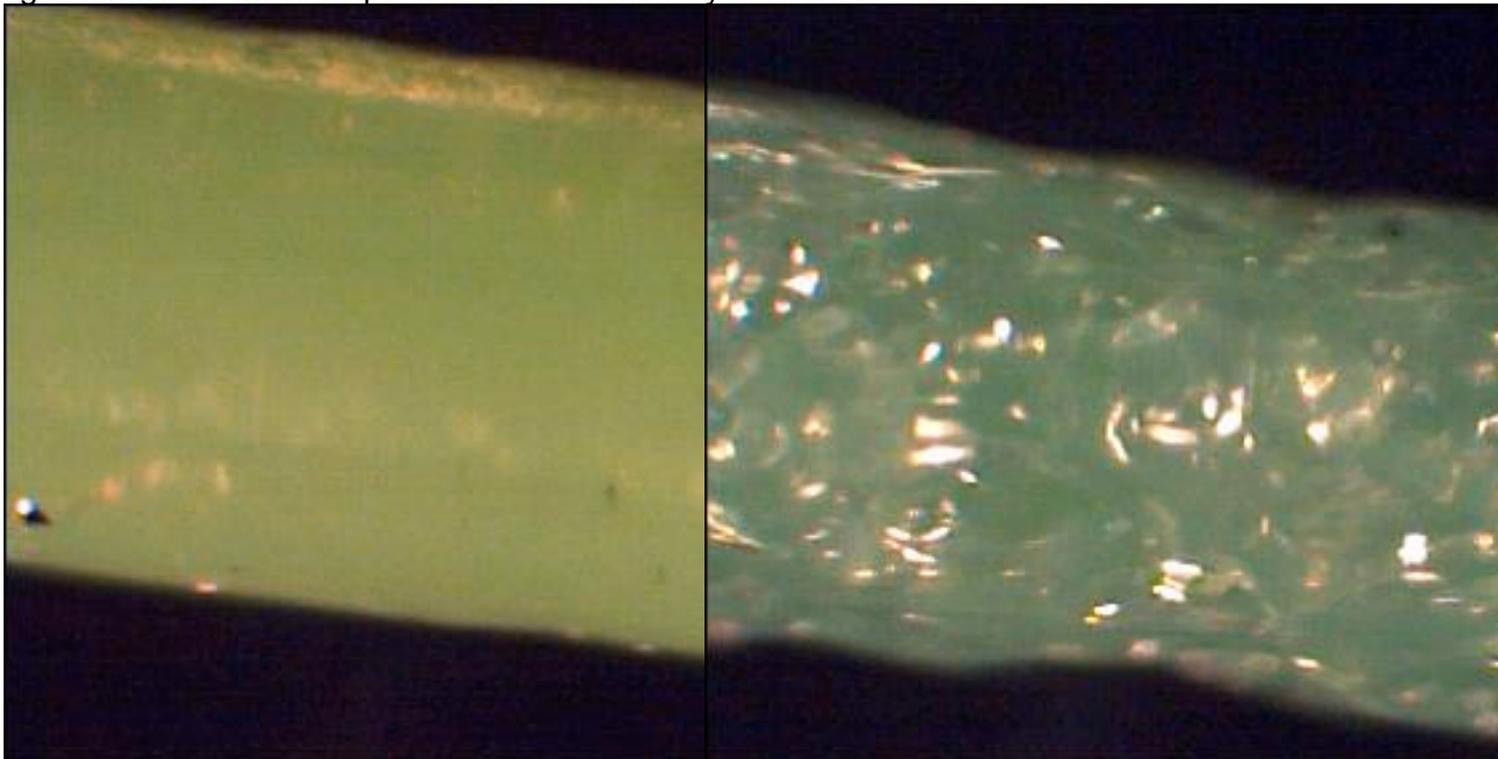
To investigate further I ran a test with the heater target temperature set to 300°C and monitored the thermistor reading. It maxed out at 290°C. That is fortunate as it is just below the point where

PTFE is supposed to start decomposing into poisonous substances. For some reason the PTFE holds up mechanically, I would have expected the barrel to pop out. Perhaps the ABS becomes so fluid that there is very little pressure required for extrusion. Anyway, the extruder seems happy operating at 280°C, where it just about manages to control the temperature with 96% PWM.

The filament changes from green and smooth to almost cyan and a rough texture: -



Again under the microscope the surface looks very different :-



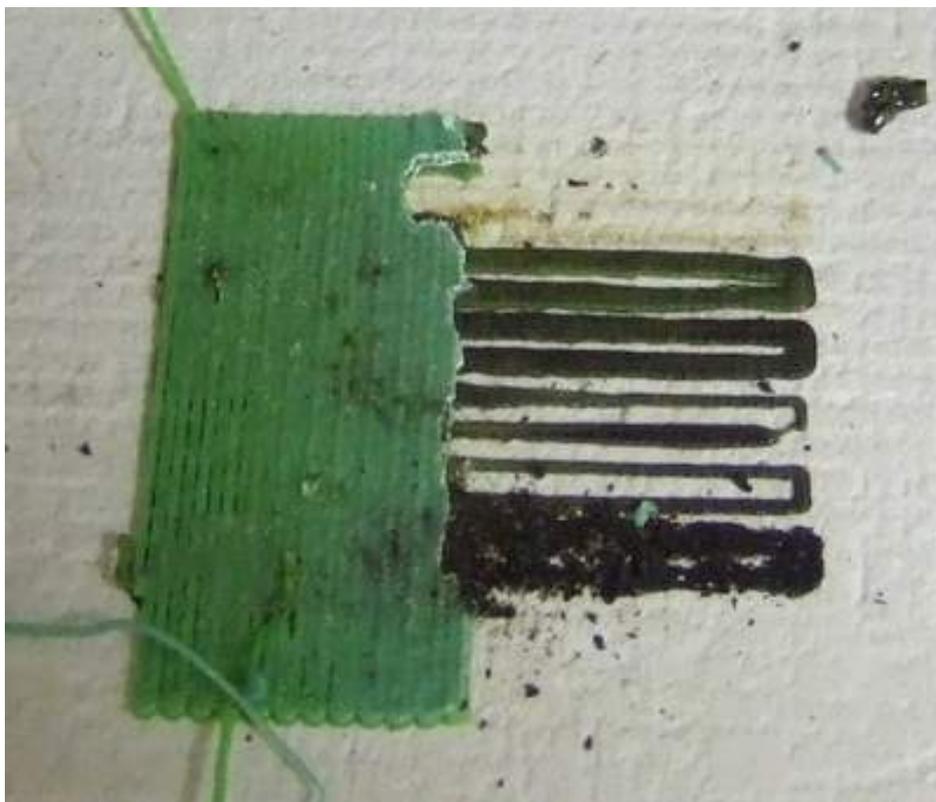
My theory as to what is happening is that the green dye is composed of yellow and cyan dyes, and the yellow component is boiling off, disrupting the surface.

I had a go at making some objects at 240°C, 260°C and 280°C :-



It seems that 240°C is about the limit for green ABS before it starts to change colour and texture. The bottom of each object has to be at the correct temperature so it can be separated from the raft but other layers could be chosen to be different temperatures to give a stripy effect. The hot objects seem very strong and feel like they wont de-laminate in a hurry.

I don't think you can keep the plastic long at those temperatures, I found this mess under a raft. I think the temperature had gone wrong during warm up.



Initially I had no idea why my temperature control was occasionally going wrong. The thermistor is still well attached. I caught the effect with some logging and discovered that the temperature was reading about 40°C low some of the time. Touching a connector seemed to fix it. I could not find a

loose connection so I just unplugged it and plugged it in again. I has been OK since. With a 10K thermistor you only need a few ohms to make a big difference at the high end.

So an interesting effect that might be exploitable for support material or aesthetic effects.

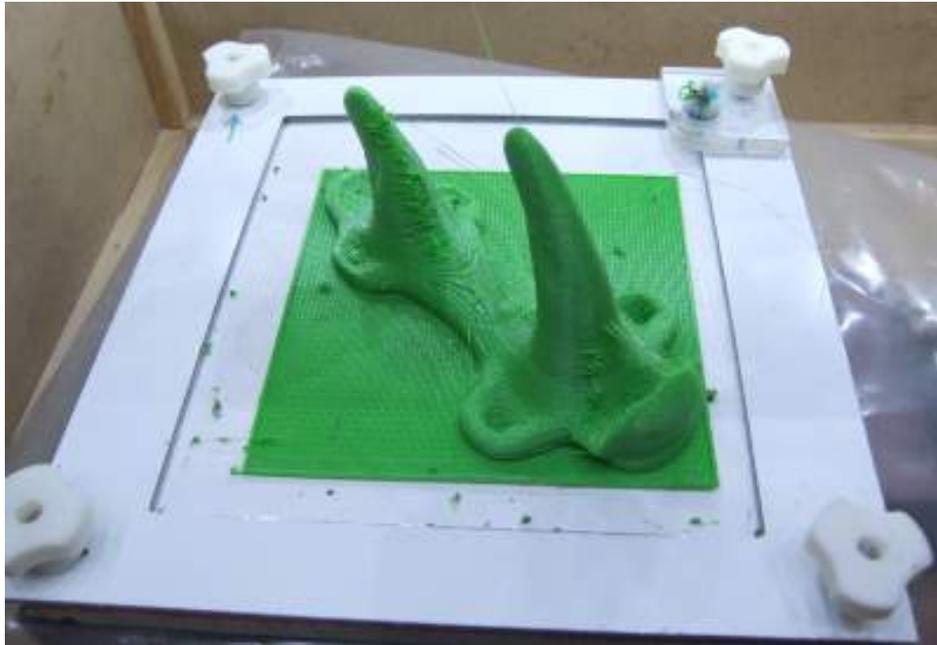
# Hat Rack

Friday, 21st November 2008 by Nophead

I came across [this object](#) designed by Gorg Huff in the RepRap objects wiki. It was such an interesting organic shape, completely different from anything else I have printed, that I had to try it.



It was a bit too big for my machine so I scaled it down and printed it diagonally.



It took about 4 hours plus an hour for the raft. Because the sides slope in quite quickly, Skeinforge switches to 100% fill for a lot of the layers because the edges don't have anything two layers above them. This can be fixed by selecting 3 extra shells on sparse layers. That means the infill starts far enough from the edge to have something two layers above it. You get a stronger object with less plastic that way.

# Lathe accessories

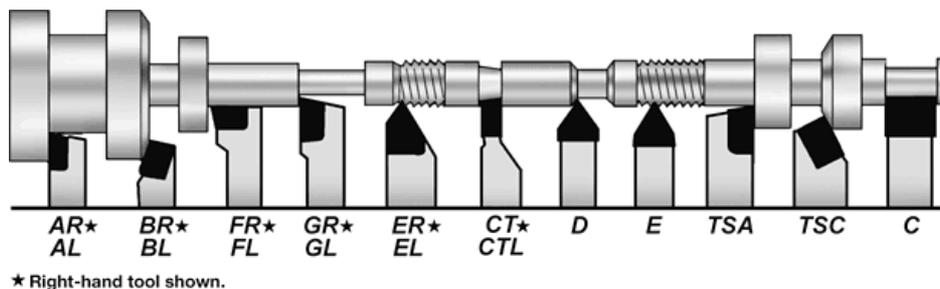
Sunday, 23rd November 2008 by Nophead

Khiralay asked me for a walk through of the lathe accessories I mentioned before, so here goes. I am no expert on lathes, I am learning as I go along. In fact, I learnt quite a lot writing this!

## Cutting tools



This is an 11 piece tungsten carbide turning tool set. I had some trouble finding out exactly what each tool is intended for. This diagram, from the McMaster-Carr catalogue, gives a good idea but doesn't exactly match the shapes.



Today I noticed that each tool is stamped with a DIN standard. Googling those mainly came up with German and Scandinavian adverts for the tools, some of them charging \$99 for one tool! Eventually I found a German site selling DIN standards. Putting in each number gives the title of the standard, which is the description of the tool.

So from left to right we have: -

1. DIN 4974 R Internal side turning tools for corner work with carbide tips.
2. DIN 4973 R Boring tools with carbide tips.
3. DIN 4980 L Offset side turning tools with carbide tips.
4. DIN 4980 R As above but right handed.

5. DIN 4978 R Offset turning tools for corner work with carbide tips.
6. DIN 4971 R Straight turning tools with carbide tips.
7. DIN 4972 R Bent turning tools with carbide tips.
8. DIN 4977 R Offset face turning tools with carbide tips.
9. DIN 4981 R Parting-off tools with carbide tips.
10. DIN 4976 Wide face square nose tools with carbide tips.
11. DIN 4975 Pointed straight turning tools with carbide tips.

1 & 2 are mounted parallel to the lathe axis and are used to bore out the inside of the workpiece. Each cut would be along the axis and successive cuts would move outwards.

8 would also be mounted parallel to the axis, but with the cut going across the face of the workpiece.

9 is mounted perpendicular to the axis and is driven into the work to cut it off from the stock. I hadn't realised it was a parting off tool, I have happily been using it to turn bearing lands with straight sides. I bought a thinner parting off blade, which wastes less material.



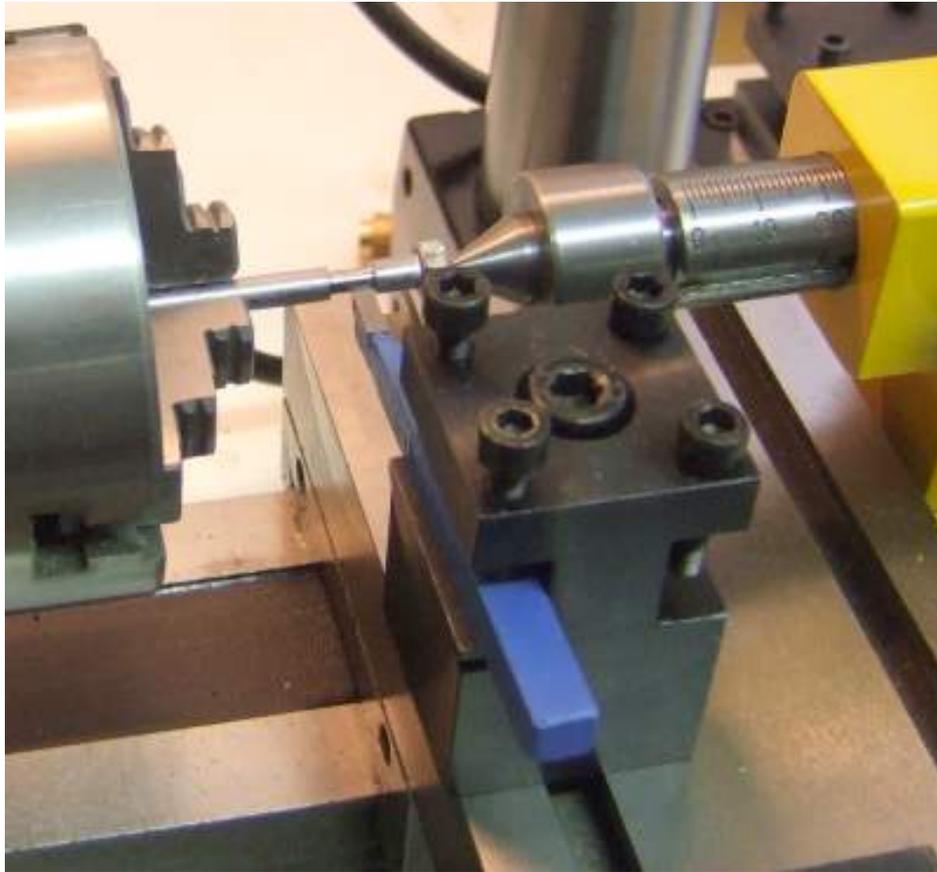
All the other tools are for mounting roughly at right angles to the axis and cutting along the outside of the workpiece.

11 has a 60° point for cutting external threads. I bought a set of gearwheels for cutting metric threads. These alter the speed of the lathe's auto feed to match the thread pitch. The procedure looks a bit complicated though, so I have stuck to using a die so far. It would be nice to be able to make large pitch ACME lead screws but that seems even more complicated.

I have had titanium nitride indexable tools recommended to me for their very long life. They have a three pointed replaceable tip. Each time a tip wears out you can rotate it until they are used up, at which point you replace it. They are quite expensive but replacement tips are not too bad.

You can also buy blank steel tools and grind them to whatever shape you want yourself.

Tools are mounted in the tool post and held down with machine screws :-



The tip of the tool must be at the same height as the centre of work. This is most easily done by aligning it against the tailstock centre. Small differences can be compensated for with the rocker under the tool by tilting it slightly. Large differences would result in the tool at the wrong angle so the other side of the post is used with a shim. The tool should be gripped as close to the working end as possible to prevent chatter.

#### Compound Slide

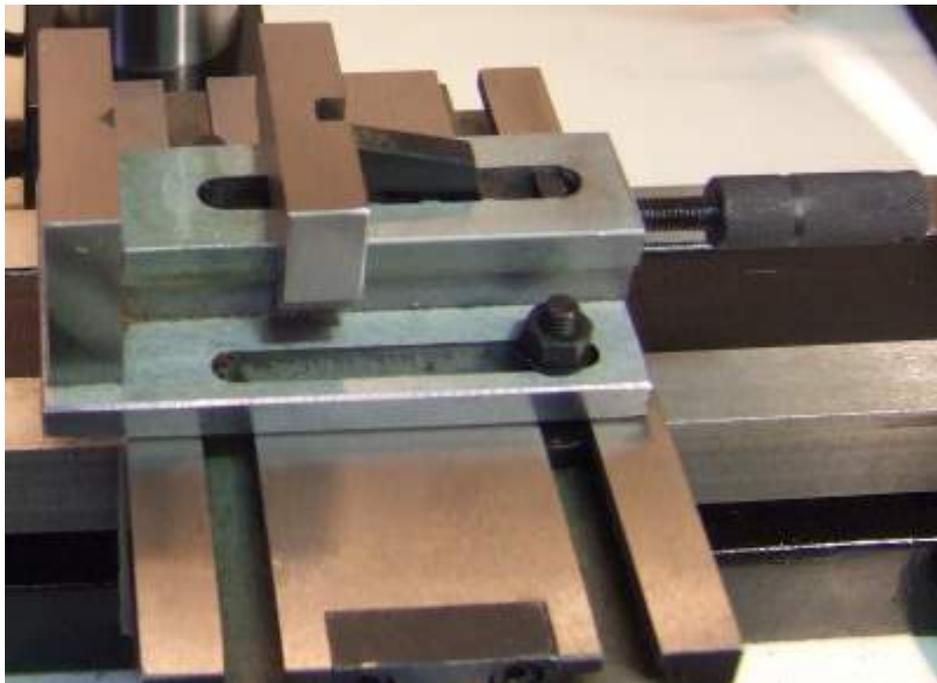
The lathe comes with a cross slide that allows you to move the tool across the workpiece and the feed screw allows motion along the axis of the lathe. To be able to cut a taper, and for cutting threads, you need to be able to move at an angle to the lathe's axis. The compound slide replaces the tool post and adds another axis of movement at any desired angle.



The next model up lathe, the CL300M, includes a compound slide, so if you take that into account the price difference is not that much. A lathe without one is quite limited, IMHO.

#### Drill Vice

I got a tiny quick release drill vice that fits on the cross slide to hold work for drilling or milling. Quick refers to the fact that rather than screw the vice all the way to open it, you lift a ratchet and drop it in the nearest slot for the width you want. Then you use the screw to tighten it no more than a quarter of its maximum travel.

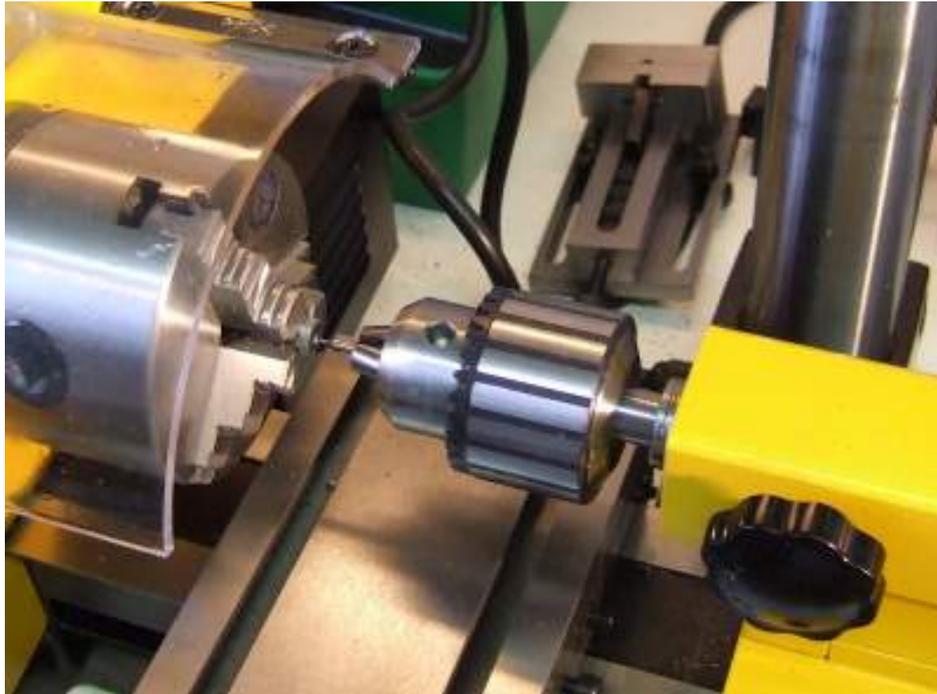


This highlights the main compromise having the lathe, mill, drill combo. The cross slide is wider

than normal for a lathe, which limits how close the tailstock can get to the chuck, but small for a milling table or a drill table. Also the height of the cross slide means that the tallest thing you can drill is not as much as you would expect from a pillar drill. If I get desperate I could remove the tailstock and cross slide, move the saddle out of the way and put a board on top of the lathe bed to drill a large object.

#### Tailstock Chuck

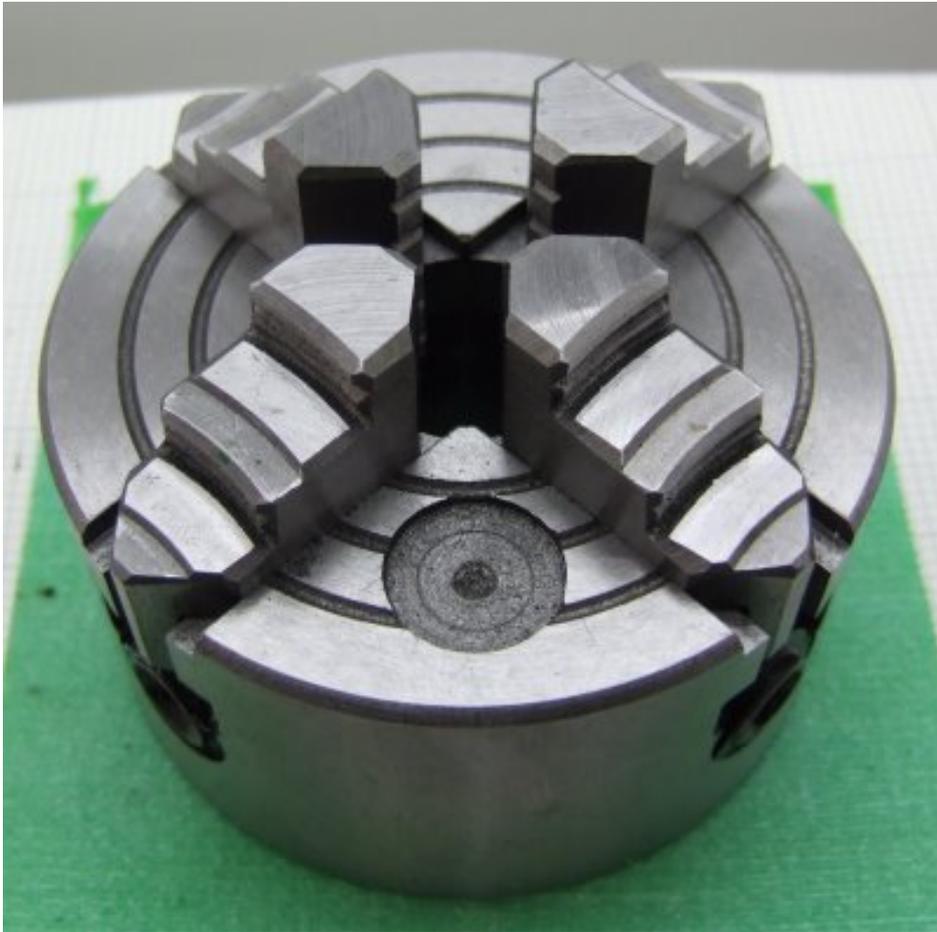
This is just a drill chuck with an MT1 Morse taper to fit into the tailstock quill. It allows you to drill into the center of the work piece. You might think holding the drill stationary and spinning the work is the same as spinning the drill and holding the work. It isn't, the former ensures the hole is exactly down the centre of the workpiece.



The chuck is exactly the same as the one the comes with the milling machine, but annoyingly that and the headstock have MT2 tapers but the tailstock is only MT1. If the tailstock was MT2 it could have shared the chucks with the milling machine, and also many other tailstock attachments, like boring heads and tap holders that only seem to go down to MT2.

#### Four Jaw Chuck

The lathe comes with a three jaw self-centring chuck. The jaws all move together to hold a round or hexagonal workpiece centrally (within the accuracy of the chuck). To hold a square or octagonal shaped object you need a four jaw chuck. These usually have jaws that move independently allowing / requiring objects to be centred manually. That also allows rectangular objects to be centred and you can also mount things deliberately off centre.



Potentially you can centre round things more accurately than you can with a three jaw chuck but it takes more time and skill.

Large, and or completely irregular shaped things can be held using a faceplate and bolts or clamps.

#### Milling Chuck

The drill comes with a normal three jaw drill chuck.



A collet chuck provides better centring and grip for milling. Expensive, but the sizes match a set of end mills I already had.



This also fits the headstock, so another way you can mill and drill on a lathe is by using a vertical slide.

#### Wiggler

This is a special chuck and a set of probes that are used for lining up the drill / mill with centre marks and edges of the workpiece.



The special chuck forms a ball and socket joint with the probe so it can swing. When you spin it in the drill chuck it rotates in a circle, but by pressing on the edge you can persuade it into a mode where it spins dead centre to axis of rotation. You use the point to line up on centre punched holes and the ball and cylinder for finding edges. The bent one is used with a dial indicator but I don't understand how or why.

Instructions for using one are [here](#). The balls are imperial sizes, which is a pain if you are working in metric units. I don't know if you can get metric ones.

#### Die Holder

This allows tapping an external thread by turning the workpiece in the chuck and holding the die with the tailstock.



The bar goes in the tailstock. The tube slides over it and can be rotated part of a turn with the handle. Different size dies can be used in each end of the holder and the two adaptors allow for two larger sizes.

I could not find one to fit an MT1 tailstock, so I had to get an MT2 one plus an MT1 to MT2 adaptor.



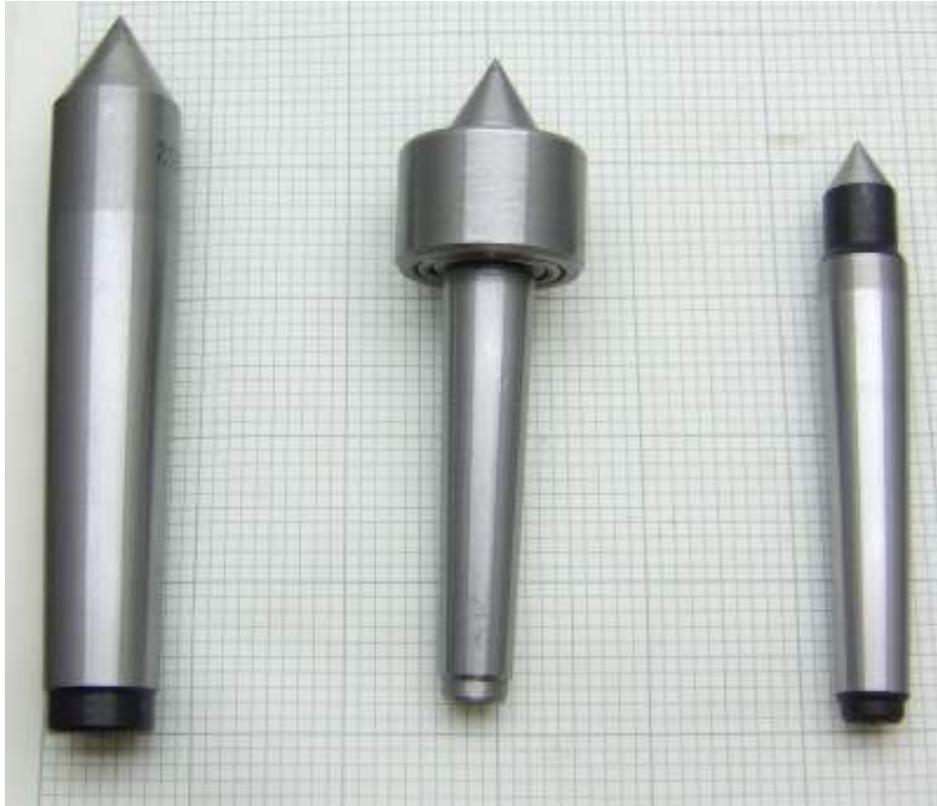
This is far from ideal because it takes up so much of the distance between centres. I ground off the tang at the end of the taper because there is nothing to engage it on my lathe. That gives me about another 10mm. I will probably bore out the end of the die holder's bar so that it will accept an M5 bar inside it. That will allow longer threads to be tapped without weakening it too much.

One other problem with the die holder was that the set screws in it do not have pointed ends. When using split dies the middle screw should have a cone shaped point so that tightening it forces the split open, allowing an oversize thread to be cut. Tightening the outer two makes an undersized thread. When tapping something hard like stainless steel you need to start oversized and then work down.

I solved the problem by turning a point on an M5 setscrew to replace the middle screw.

I should really have made one of these, I think, rather than buying this one that is too big. It should be fairly straightforward to make on a lathe. I don't fancy turning an accurate MT1 taper but you can buy Morse tapers with a soft blank on the end for machining to a custom use.

## Centres



The MT1 tailstock centre of the right came with the lathe and is known as a "dead centre" because it does not rotate. The one in the centre is a "live centre" because it has a bearing, which allows it to rotate with the work, reducing the friction. There is also a variant called a "half dead centre" which is a dead centre with half the cone cut away to allow a facing tool to get in.

I also got an MT2 dead centre to fit the headstock or my MT2 adapter.

Some good reference material: -

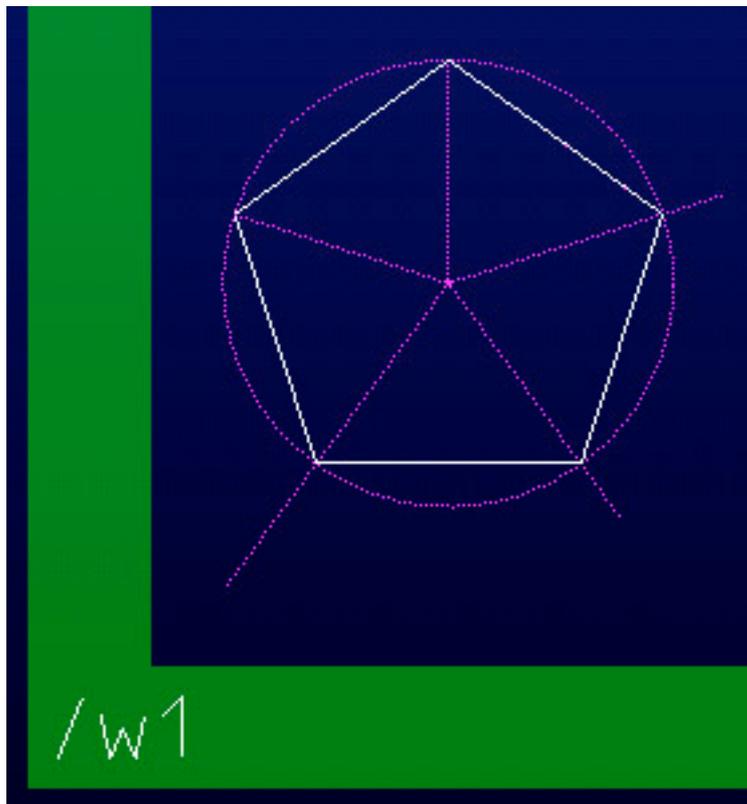
[www.americanmachinetools.com/how\\_to\\_use\\_a\\_lathe](http://www.americanmachinetools.com/how_to_use_a_lathe)  
[myweb.tiscali.co.uk/silkstone/minilathe/minilathe01](http://myweb.tiscali.co.uk/silkstone/minilathe/minilathe01)

# Dodecahedron

Tuesday, 25th November 2008 by Nophead

I fancied making a dodecahedron, an object with twelve pentagonal faces. It is an interesting shape and, as the sides slope at  $\sim 26^\circ\text{C}$ , it can be made without support material. I searched the web for a 3D model for some time but could not find one. I also searched for how to model one in CoCreate, as it wasn't immediately obvious to me. That came up blank as well so I had to figure it out myself.

I started with a construction circle and divided it into 5 sectors with construction lines  $72^\circ$  apart. I joined the intersections to make the base pentagon.



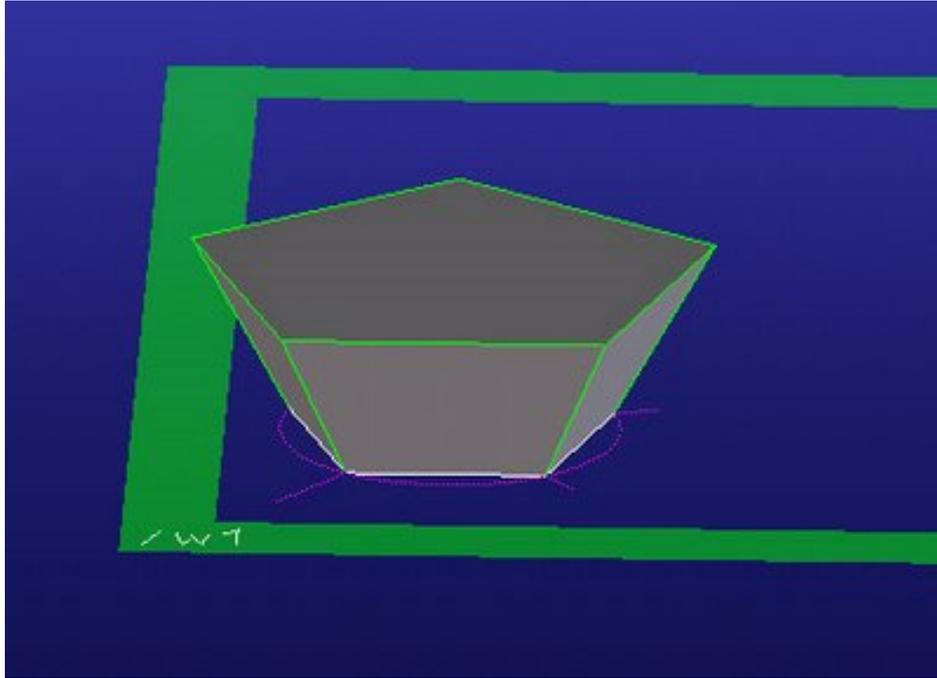
I then extruded that to a height equal to the circle radius and with a draft angle of  $-26.56505^\circ$ . This is the dihedral angle



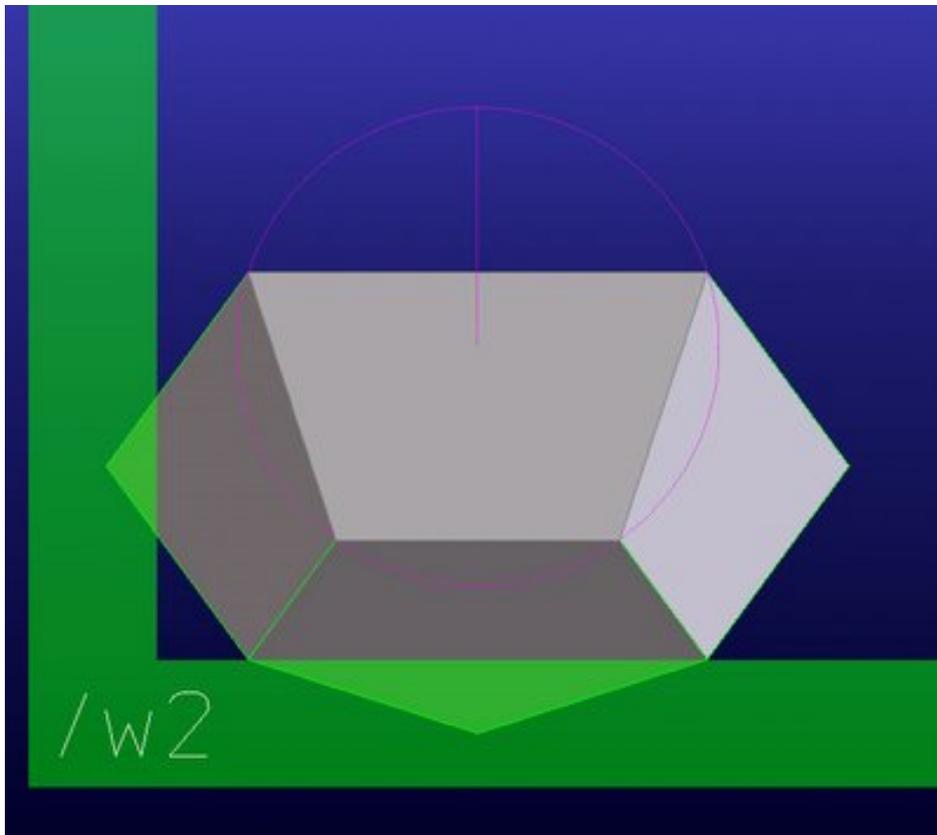
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$(2\arctan((1+5)/2))$  minus  $90^\circ$ . That makes the base of the object and the first line of vertices

above it.

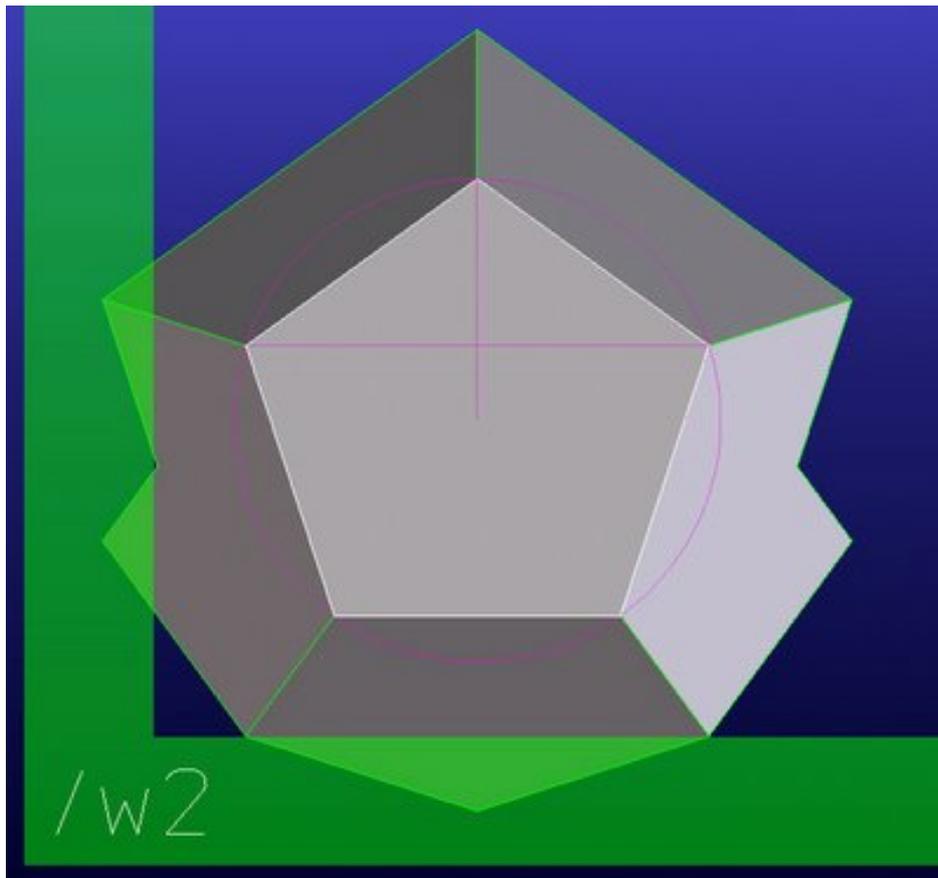


I then made a new workplane on one of the partial faces. I projected the face onto the workplane and then added a construction circle through three of the points. A vertical line from the centre gives the missing fifth vertex where it meets the circle.

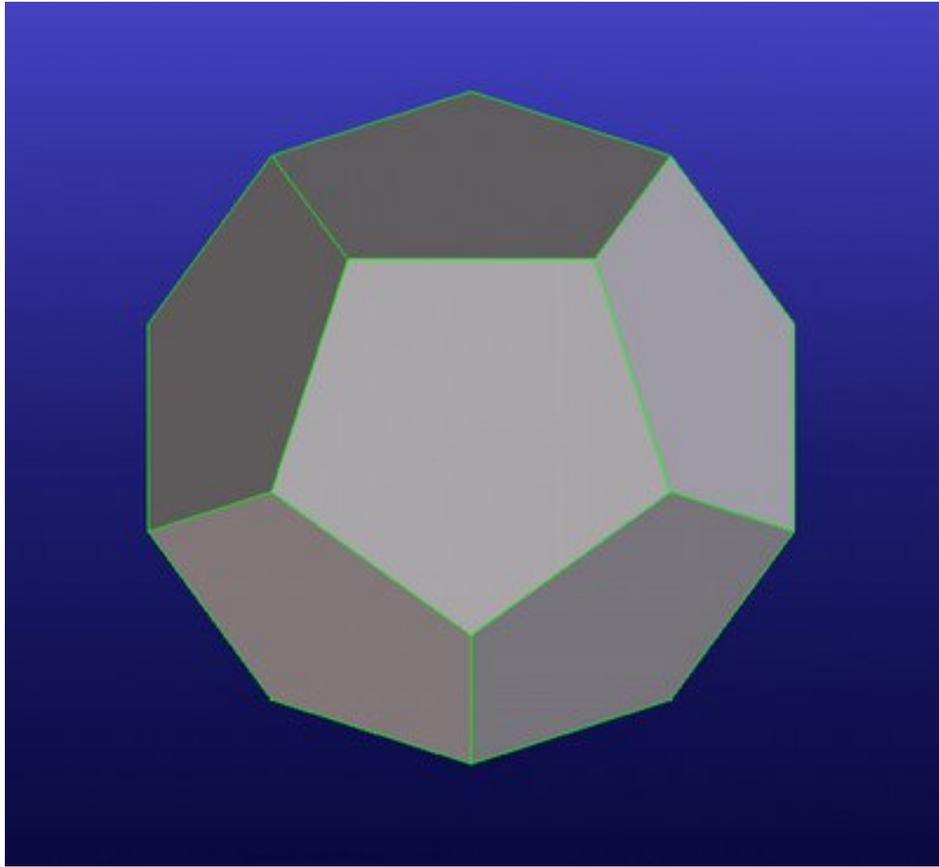


I then join the vertices to make the pentagon, extrude it inwards (negative) by the circle radius with

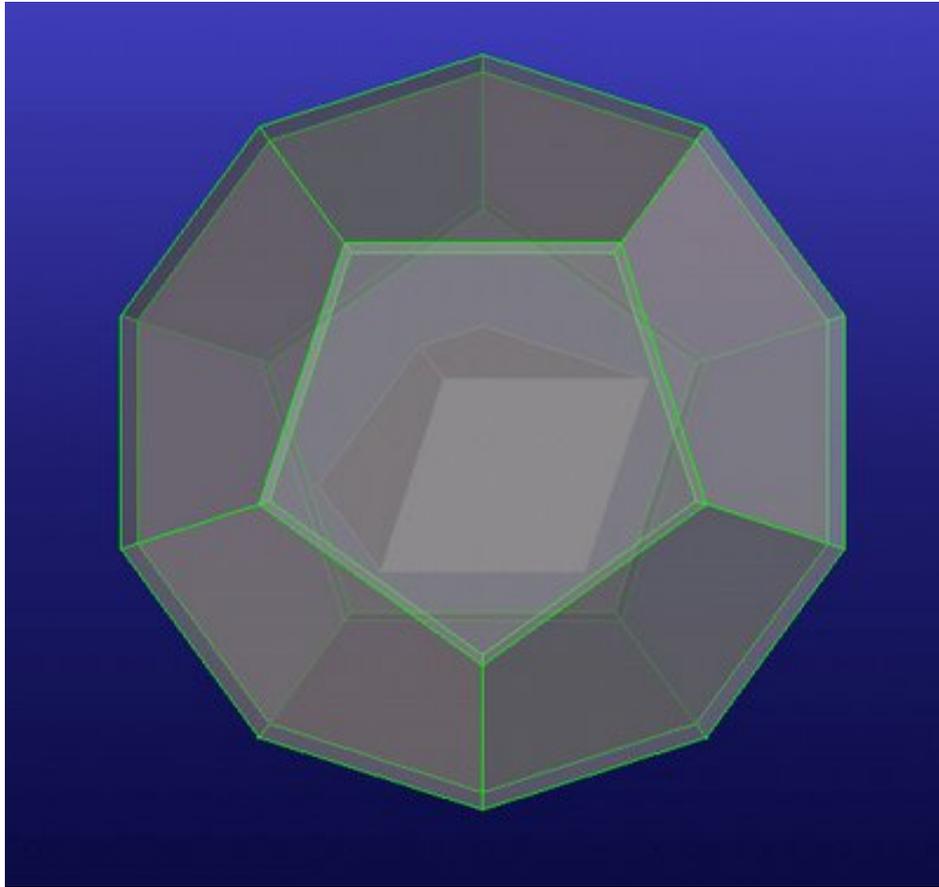
the same negative draft angle.



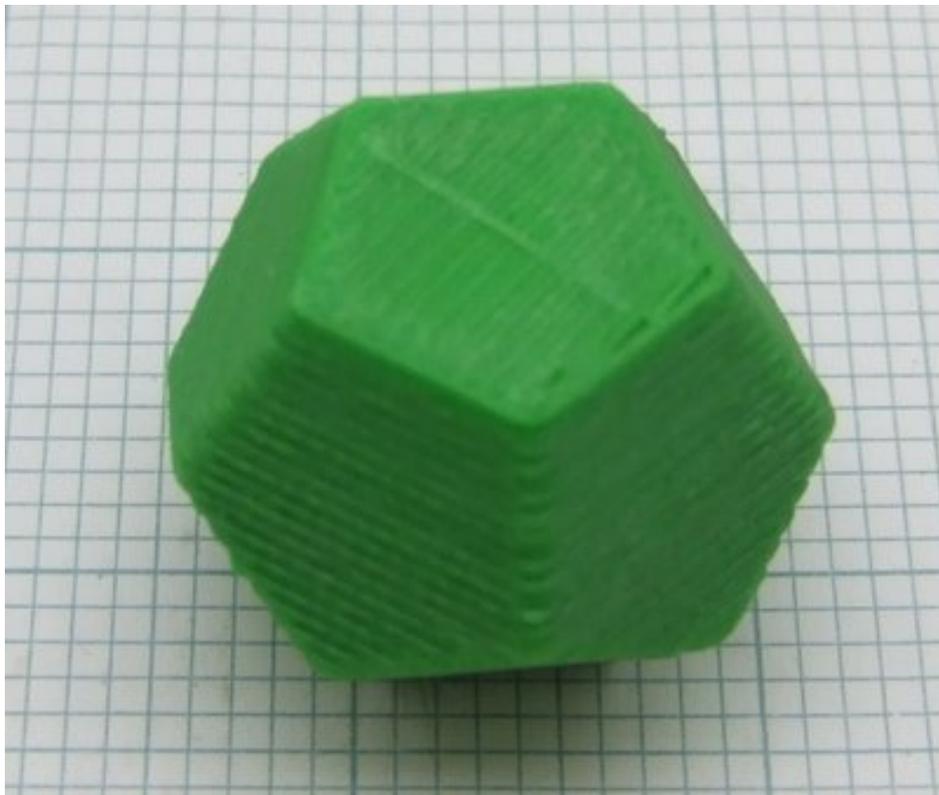
That operation has generated two partial faces with all five vertices. I construct the pentagons from the vertices and extrude inwards by the circle radius until the shape is complete. A total of eight extrusions are required.



I then shelled the object to 2mm to make it hollow. That created a second part inside, revealing that the construction does not in fact make a complete solid. If that was important one could extrude one of the faces more than half way through, with no draft angle. I just deleted the second part.



The finished item is about 2.5 times initial circle radius across opposite flats. This one was based on a 10mm radius circle.

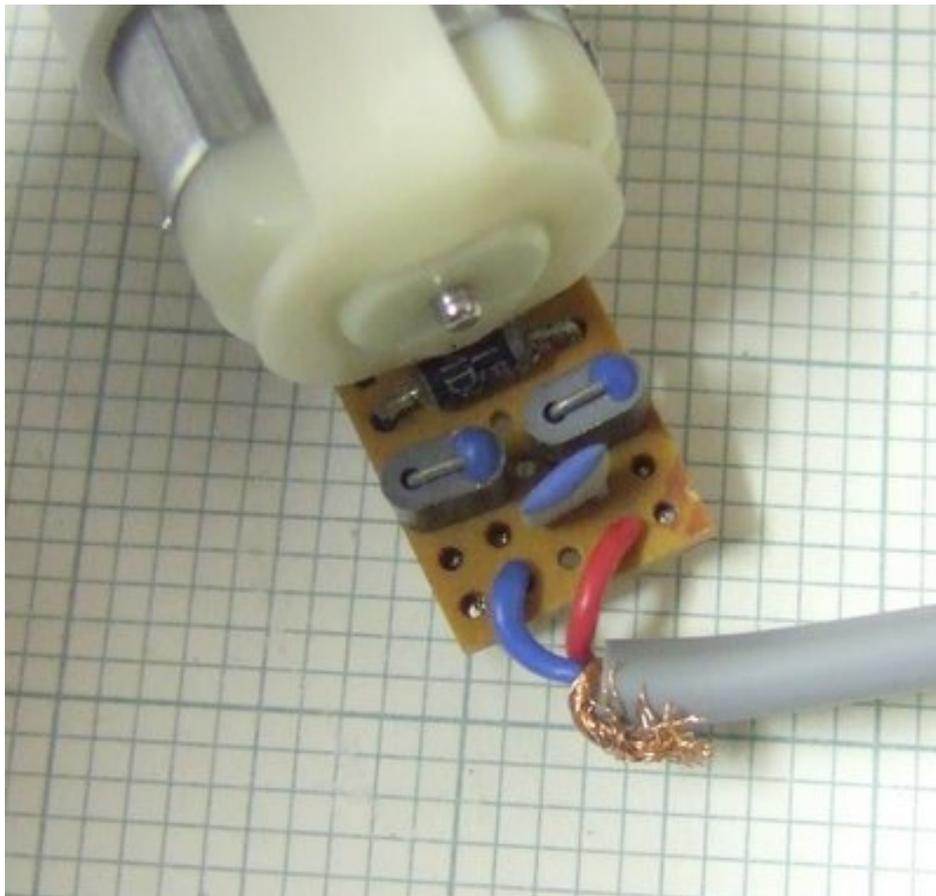
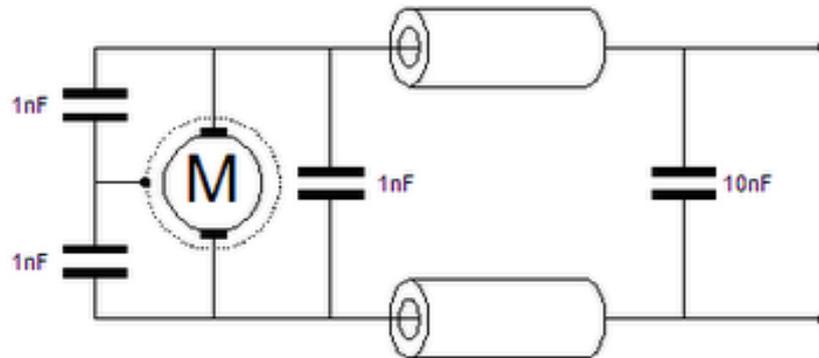


The file is available on [Thingiverse](#).

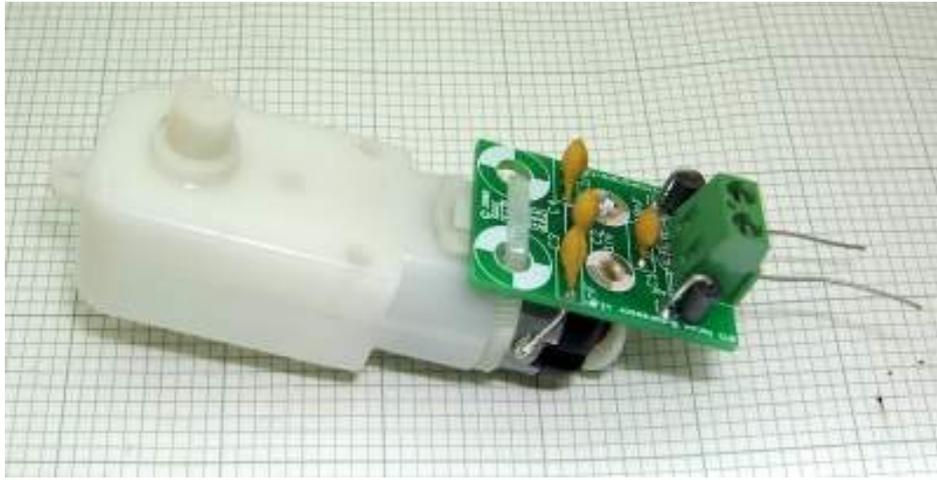
# Suppression

Sunday, 30th November 2008 by Nophead

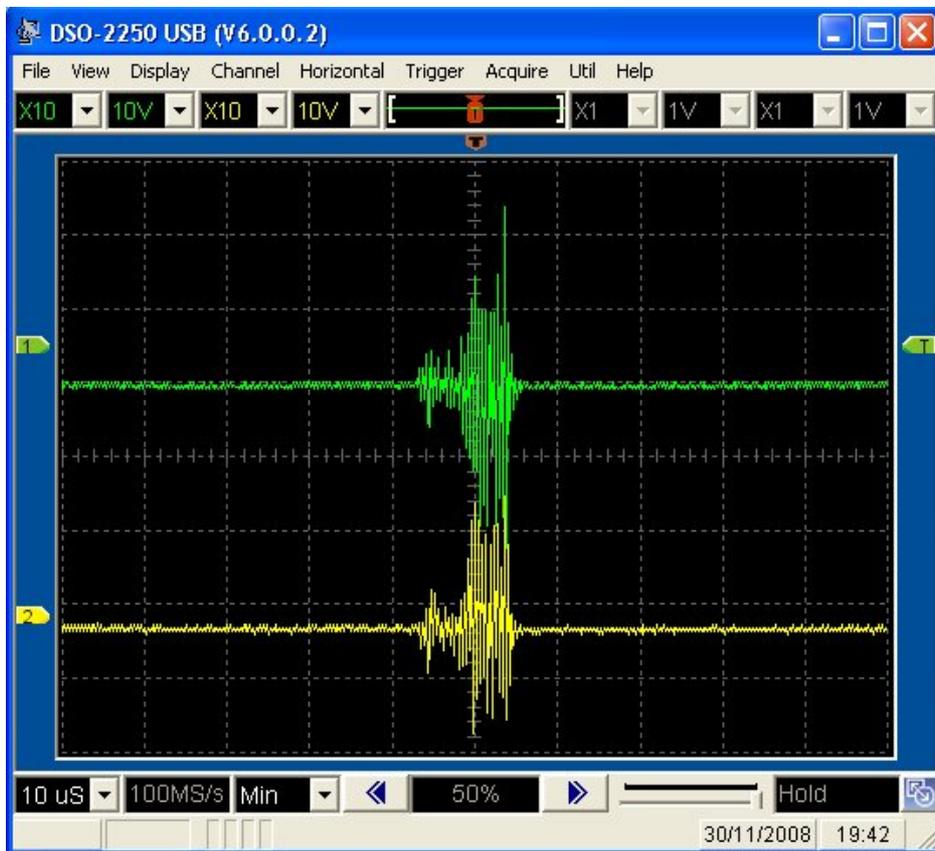
Some time ago I [blogged](#) that the GM3 gearmotor generates a lot of RFI, which was interfering with TV reception in our house and corrupting I<sup>2</sup>C comms on HydraRaptor. I designed a simple suppressor that fixed the problem, details [here](#).



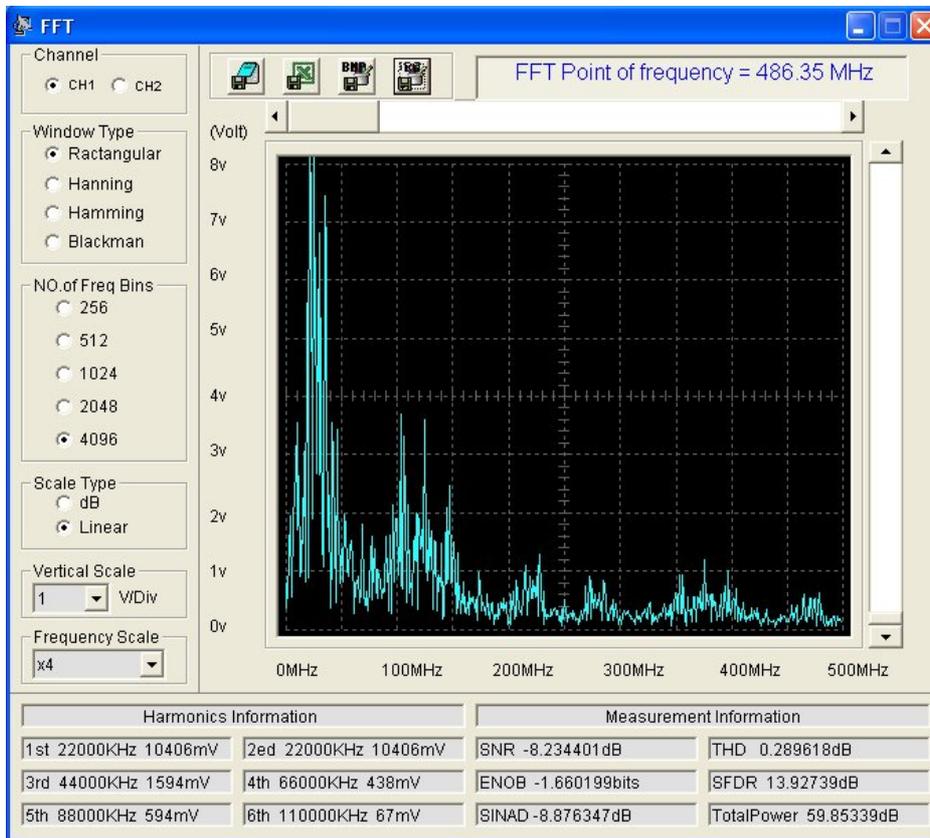
Recently Zach Smith designed a [nice little PCB version](#) of it and produced a kit. He gave me a sample to test. Here it is installed on a GM3: -



To test it I wired a GM3 with no suppressor to a bench power supply with a pair of jumper cables about 30cm long. I viewed the noise on both motor terminals with a scope grounded at the PSU. This is what it looks like in the time domain.

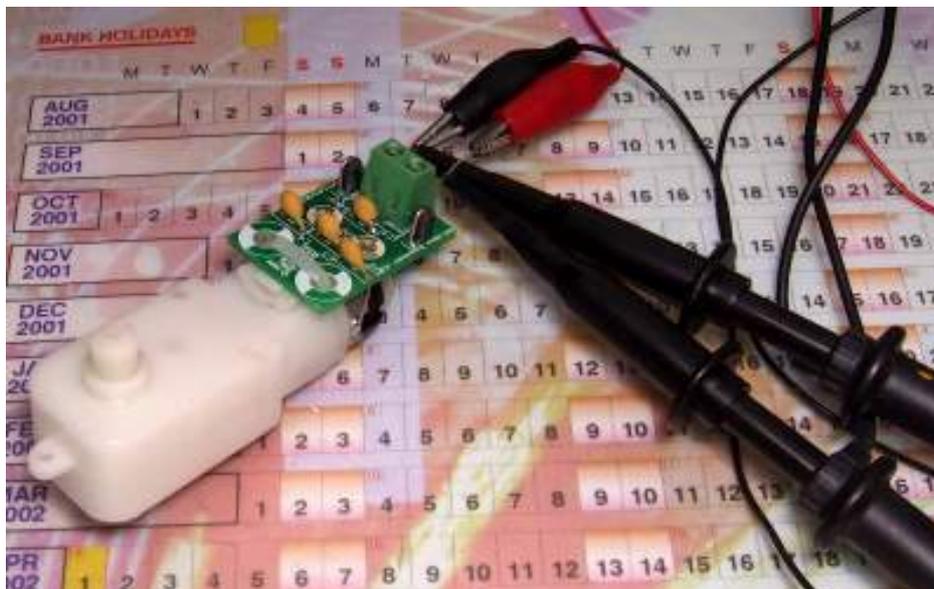


It is massively noisy producing about 50V pk-pk. And here is the spectrum in the frequency domain: -

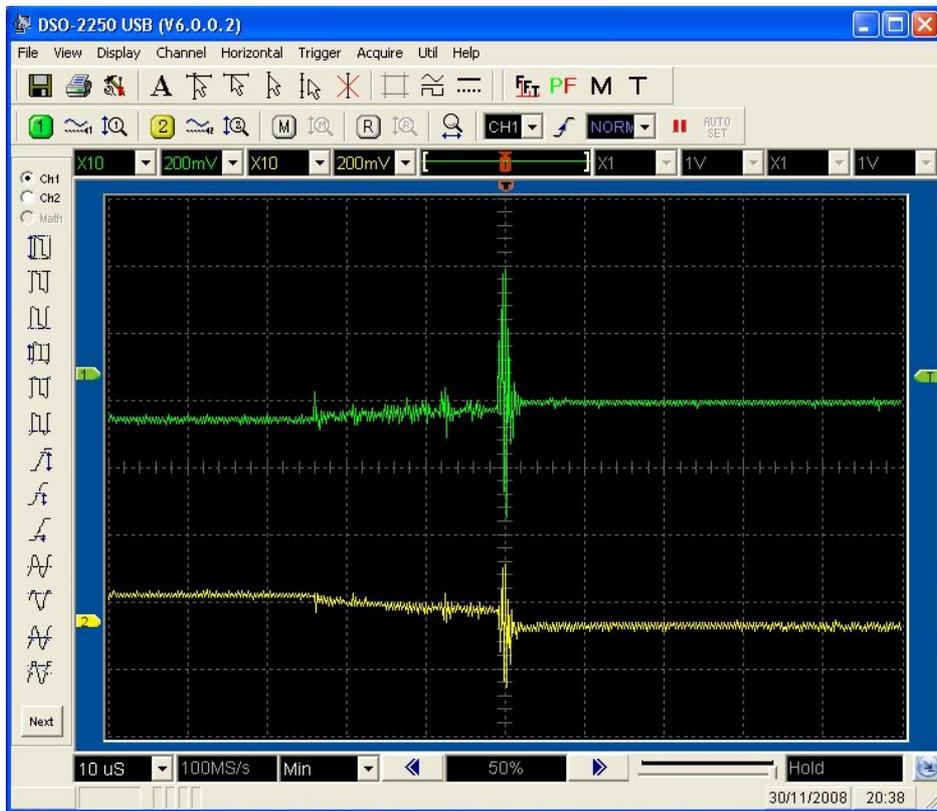


Although this is the 12V version of the motor it looks similar to the 6V version I tested before.

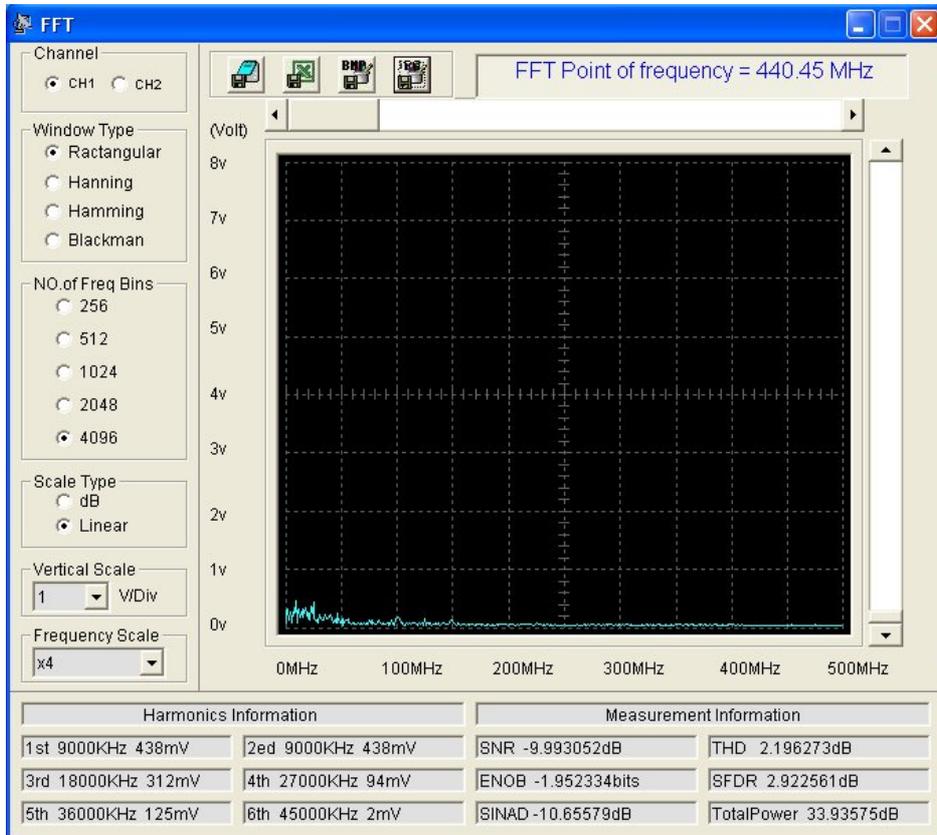
I repeated the same test with the suppressor fitted, measuring the voltage at the terminals of the suppressor.



The noise is vastly reduced, now only about 700mV pk-pk.



The spectrum is reduced drastically as well: -



Compared to my Vero board version, tested under the same conditions, it seems to work a bit better, but that could be down to variations between motors.

So the kit version works well and also gives convenient screw terminals or 0.1" header robustly anchored to the motor.

# Sticking point

Sunday, 21st December 2008 by Nophead

sid, who is a regular contributor to the RepRap forums, had an idea to get a soldering iron manufacturer to make a heater barrel assembly for RepRap. He approached a Chinese company with a specification and they sent him some prototypes. He forwarded one to me for testing. It appears that they ignored his specification and just sent a standard de-soldering iron element. Nevertheless it is a nice unit and looks eminently usable.



It has a tube running through the middle with an internal diameter a shade over 3mm. Ideally it needs to be about 3.5mm to cope with the worst filament I have encountered. My green ABS, being a little undersized, fits down it easily.

The heater has a cold resistance of 1.3 but, unlike nichrome, it has a big temperature coefficient, so its resistance increases significantly as it gets hot. It appears that it is a 12V 50W heater. We can drive this with PWM using a MOSFET provided the PSU can handle 9A peaks on the 12V rail in addition to what the steppers take, a tall ask. An inductor and diode could be used to reduce the peak current.

The other two wires are a type-E thermocouple. Unfortunately the thermocouple sensor board that Zach designed using the AD595 is for the more common type-K thermocouples. It can be recalibrated for type-E by adding extra resistors. However, the AD595 is an expensive chip because it is factory trimmed for accuracy. By the time you add external components the convenience and accuracy is lost so you might as well just use a cheap op-amp and a micro with

an internal temperature sensor for the ice point compensation. E.g. the MSP430F2012 that I use for my extruder controller is a lot cheaper solution than the AD595 and can control the heater and motor as well.

To test the heater I clamped it by the mounting flange in a vice and hooked it up to a bench power supply. I measured the internal thermocouple's output with a millivoltmeter and also inserted a 3mm rod type-K thermocouple down the barrel. Here are the results: -

<u>Voltage</u>	<u>Current</u>	<u>Power</u>	<u>Resistance</u>	<u>Temperature</u>	<u>Thermocouple</u>	<u>Calculated</u>
					<u>e</u>	<u>Temp</u>
1 V	0.75 A	0.8 W	1.3 R	43 C	1.5 mV	42 C
2 V	1.20 A	2.4 W	1.7 R	106 C	5.6 mV	102 C
3 V	1.55 A	4.7 W	1.9 R	182 C	9.5 mV	160 C
4 V	1.80 A	7.2 W	2.2 R	275 C	14.5 mV	233 C
5 V	2.00 A	10.0 W	2.5 R	357 C	20.0 mV	314 C

The temperature column is as measured with my type-K thermocouple towards the nozzle end of the barrel. The calculated temp column is assuming  $68\mu\text{V}/^\circ\text{C}$  from the type-E thermocouple and a cold junction temperature of  $20^\circ\text{C}$ . There is a big temperature gradient along the barrel so the thermocouple reading depends on where it is placed.

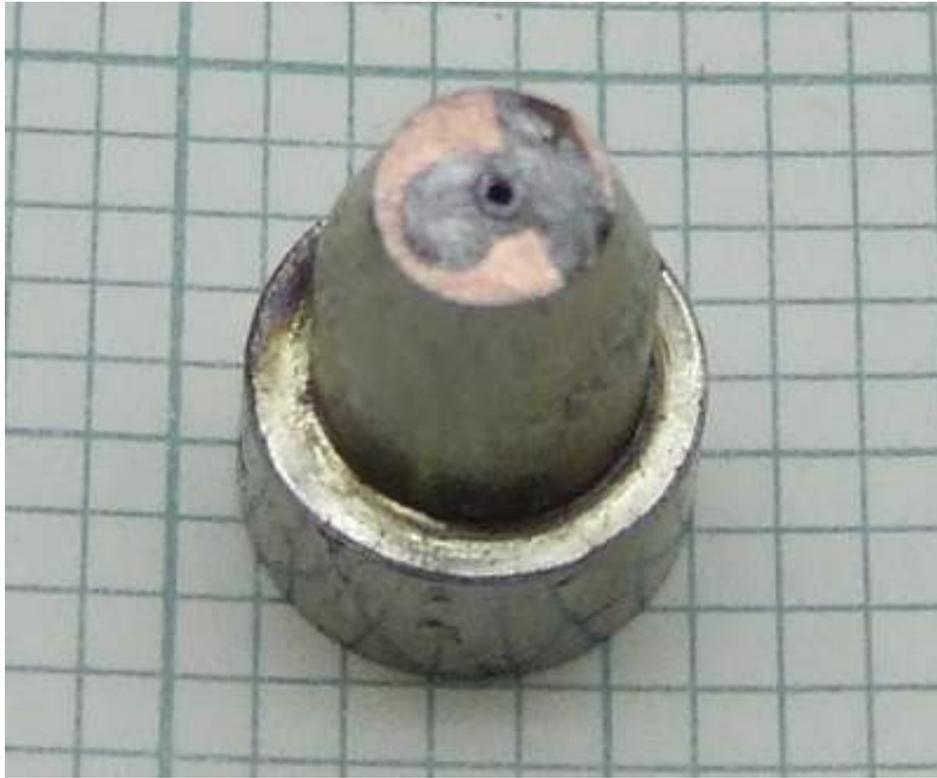
As you can see we only need about 5V to drive the heater. The current would start at 3.8A and fall to 2A as it warmed up. This would be kinder to the PSU and safer than using 12V, but 12V would give a much faster warm up time. I expect something better than bang-bang control would then be needed to avoid massive overshoot.

When running horizontally the inlet tube stays cold and the mounting flange is just too hot to hold so it would be ideal for mounting to ABS or HDPE. This is because the barrel appears to be stainless steel, which is a very poor conductor of heat. The element must be towards the bottom so there is a continuous thermal gradient along the barrel.

The nozzle that came with it is made from copper with some type of plating. It had a hole to mate with the tube that sticks out of the end of the heater but it did not go all the way through. In fact it could not, as the tip comes to a fine point. I suspect this is a soldering iron bit that has been drilled out to fit.



I attempted to drill a 0.5mm hole through it but it just snapped the drill. Even drilling a 1mm hole snapped the drill. In the end I drilled a 2mm hole, but the drill bent and came out the side. I think it needed to be sharper for copper. Finally, I cut the point off and filled the 2mm hole with high temperature solder. That is soft enough to easily drill a 0.5mm hole through. It melts at 300°C so should hold up.



The heat damage is where I heated it up with a blow torch in an attempt to remove the broken drill bits. Copper expands a lot more than steel. That did not work so I tried to get it red hot to soften the drill bits so I could drill them away. I failed to get it red hot but I did melt the plating.

The shape is not ideal for making objects but it is good enough to see if I can extrude. In fact it extrudes well. I was able to push a piece of ABS through it easily by hand and it extruded at a very good rate.



The bit/nozzle is clamped on to the end of the barrel by an outer stainless steel sleeve tightened up by a threaded ring at the cold end. I was worried it would leak under extrusion pressure without some sealing. When I stripped it down I found it did leak a little but didn't get far. I suspect it freezes when it meets the outer sleeve.



So apart from the bore being a little too small this seems like a perfect solution: -

- It needs no construction apart from drilling the nozzle.
- It is mechanically sturdy.
- It should be very durable; soldering irons last a lifetime and they run at higher temperatures.
- It is cold enough to mount with plastic without any insulation. It does after all in a soldering iron although that is probably a thermoset plastic.
- The nozzle can be easily removed and replaced.

BUT, it has one fatal flaw, exactly the same flaw as my attempt to use stainless steel as a heat barrier in my experimental high temperature extruder. There is a slow thermal gradient along the length of the barrel. That means there will be a point about half way along where it is just hot enough to soften the plastic but not hot enough to make it flow. When you push a piece of virgin filament in it slides past that point easily because it does not have time to soften until it gets to a much hotter part of the tube. If however you stop extruding then the stationary filament has enough time to soften further up. When you push it again it expands to plug the tube but is not fluid enough to move. No matter how much force you apply you cannot move it. To get it going again you have to pull it out backwards, cut off the swollen bit and start again.

The reason the original extruder design does not have this problem is that the thermal gradient is in the PTFE. It is much shorter so the problem region that is soft but not molten is a lot shorter and the walls are very slippery so it can still be shifted.

I can't think of a solution to this problem. You could make the internal tube out of copper but then the top end would be hot so you would need a PTFE thermal break again. Also it would not be an off the shelf product, it would be custom to RepRap. Perhaps a taper at the problem region could stop it sticking.

The next extruder I am building has an aluminium barrel and nozzle and a PEEK thermal break. It won't suffer from this problem at least.

# New Materials

Friday, 26th December 2008 by Nophead

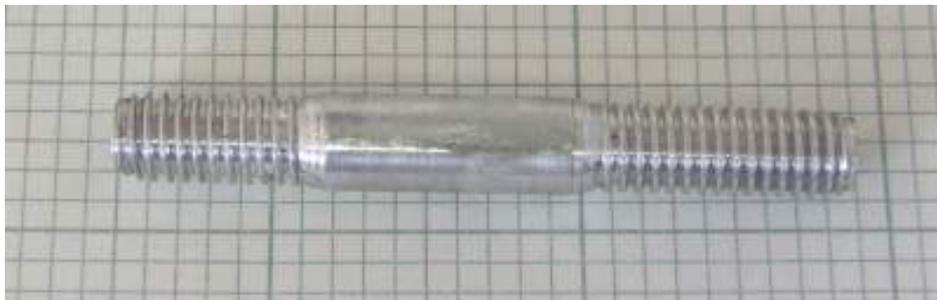
HydraRaptor's extruder suddenly stopped working in the middle of a build a few weeks ago. I tried upping the temperature and pushing the filament with pliers but it would not budge. All that happened was the heater barrel slipped a few threads in the PTFE insulator.

It was a bit difficult to find out what was wrong because it was full of solidified plastic when cold. I unscrewed the nozzle and placed it in some acetone to dissolve the ABS. It appears that the hole in the nozzle was blocked by burnt plastic. It probably formed when I had some high temperature accidents and experiments recently.

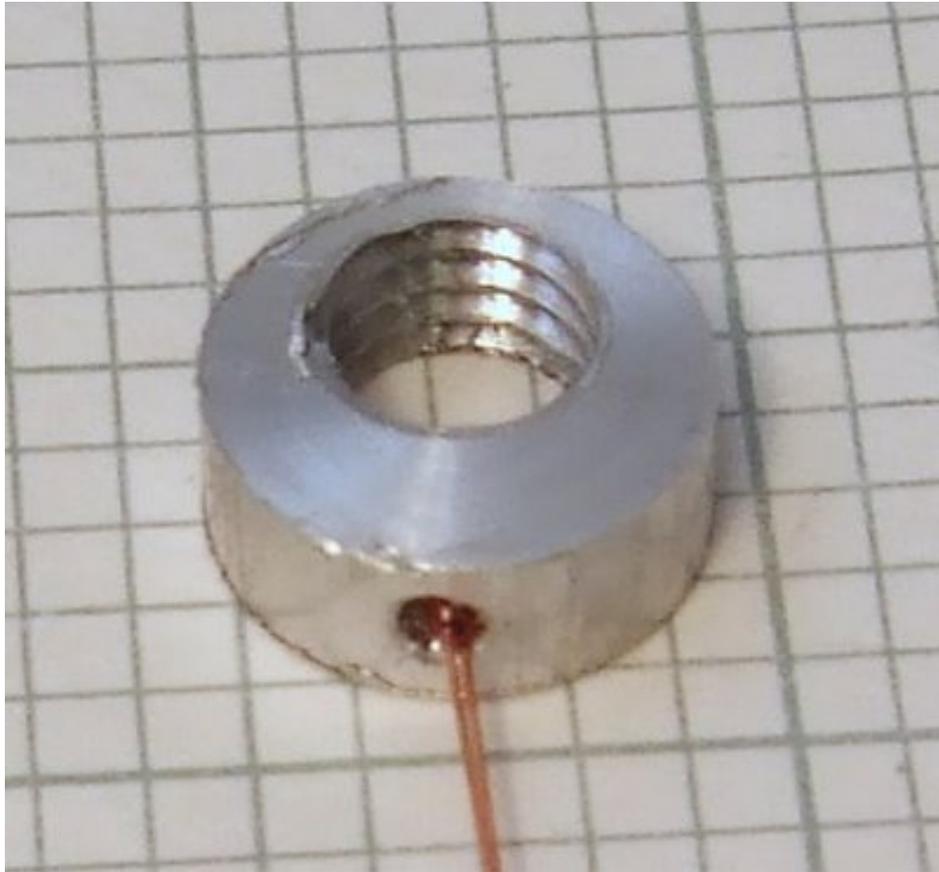
I should have realised the nozzle was blocked, but it has never happened before. If I had then I could have just unscrewed it, cleaned it out with acetone and put it back on again. In the event pushing the heater out of the PTFE pretty much wrote it off.

Not for the first time, I decided to rob parts from the extruder I was making for my Darwin. These are all made from different materials in order to see if small improvements could be made.

The barrel is made from aluminium. It is a better thermal conductor than brass, is easier to machine being a lot softer, and is cheaper.



To make the thermistor more easily removable I mounted it in ring of aluminium with a tapped hole.



The thermistor was glued in with Cerastil H-115 and the ring was screwed onto the barrel with some heatsink compound in the thread. By adjusting the beta I was able to get the reading to agree with a thermocouple inside the barrel to within a couple of degrees. I don't know if that means the ring was at the same temperature as the middle of the barrel or if it was lower and I compensated with a beta value that is not actually the beta of the thermistor. Either way it produces the desired result.

I also made an aluminium nozzle with a 0.3mm aperture. I broke the drill bit as it went through. I am not sure if that was due to the aluminium snatching more than brass does, or me being careless. I have broken loads of small drills recently and blunted some bigger ones by accidentally drilling with my lathe in reverse!



The picture also shows where the thermistor ring mounts.

Another modification I made was to put a PTFE cap over the nozzle.



This has two benefits: -

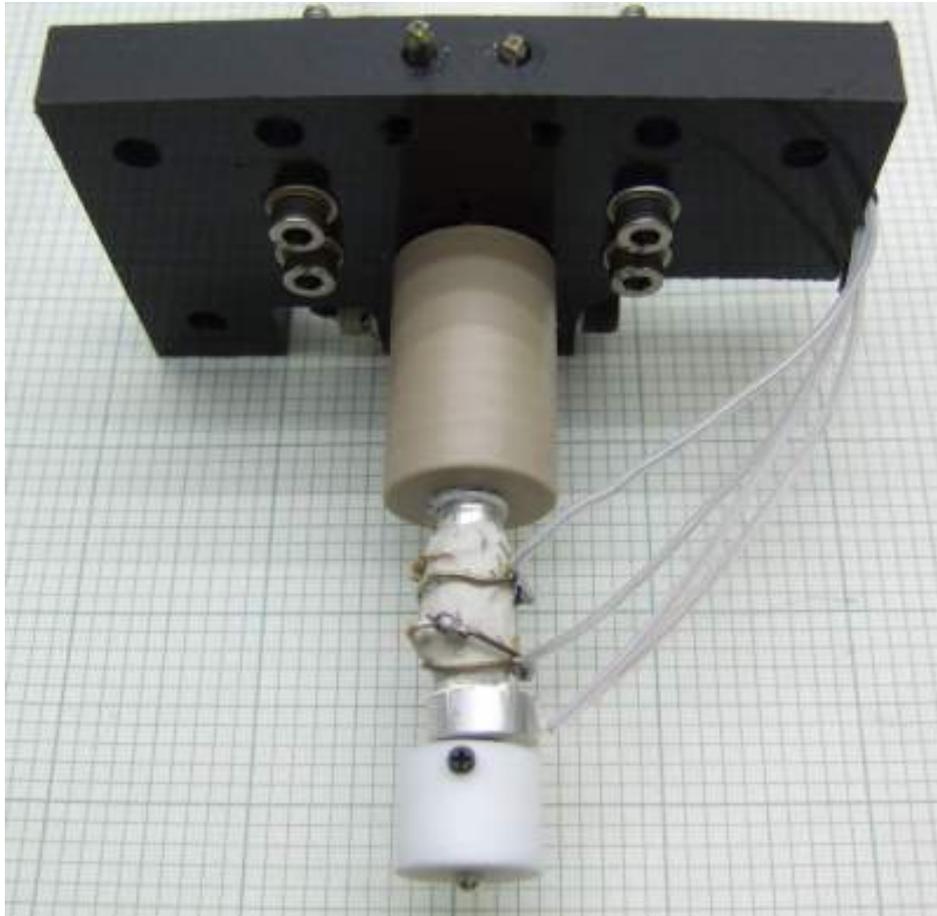
1. It is a good insulator so it helps to keep the nozzle warm.
2. Being non-stick, and also cooler than the nozzle surface, it stops filament from sticking to it. I use a brush to wipe the nozzle. This works well with HDPE but ABS tends to curl upwards and stick. Since I added this cap the nozzle wipe has worked 100%. It remains to be seen if it works with PCL and PLA.

It is a snug fit but when it gets hot PTFE expands a lot so it slips off. I held it in place with a tiny screw and an indentation in the nozzle made with a drill point.

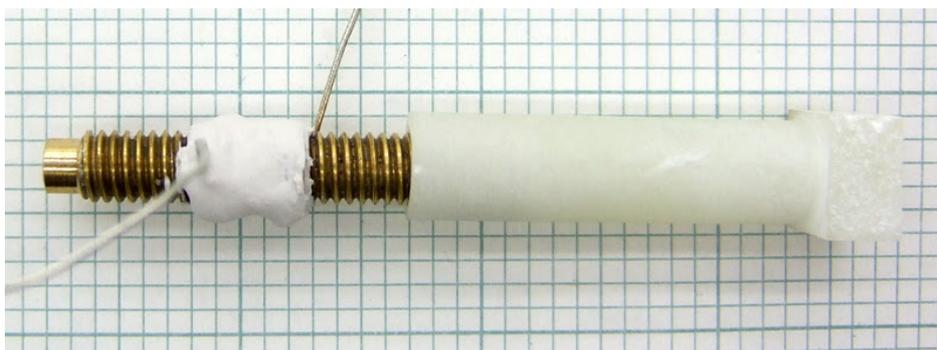


Another new material I used was Polyetheretherketone (PEEK) instead of PTFE for the thermal break. This has similar insulating properties to PTFE and a slightly better working temperature range. It machines well but forms burs very readily.

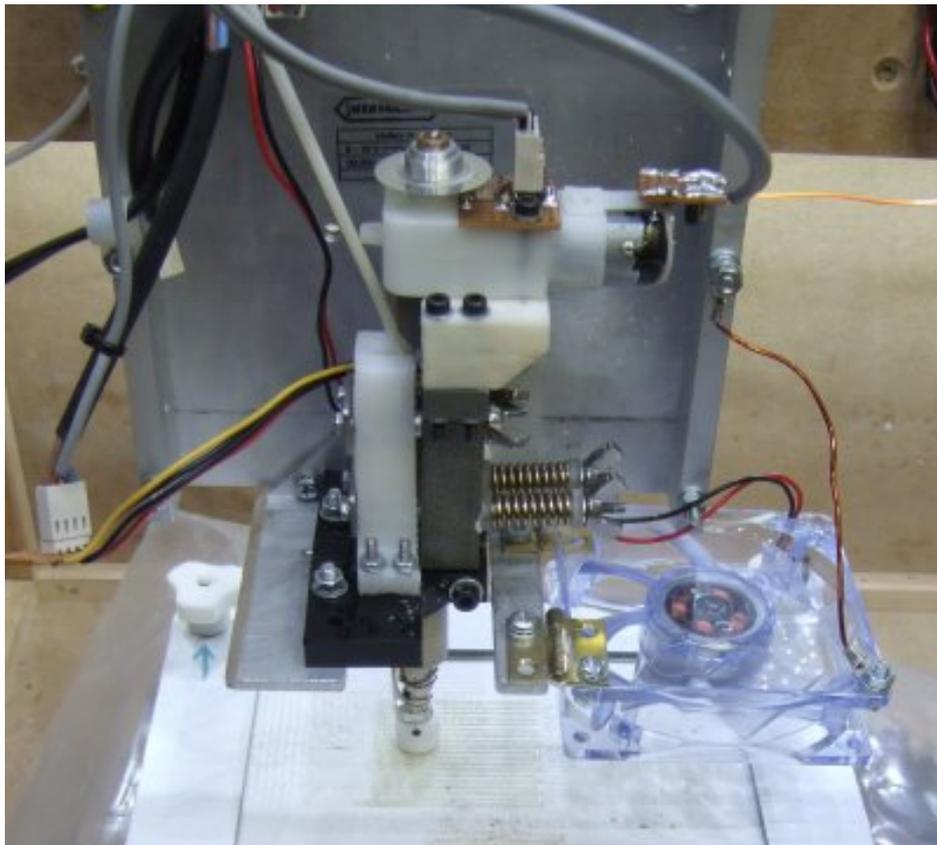
I found it much sturdier at working temperature, I don't need a pipe clip to stop the barrel popping out now, but I think it may be a bit harder to push molten plastic through, being less slippery.



The other thing I changed was I used insulated nichrome. When using bare nichrome I have to put down a thin layer of Cerastil to insulate the barrel, leave it to set, then wind the heater and cover it with more Cerastil. That makes it a two day job. By using insulated nichrome I can just wind it straight on the barrel and then cover. But what I didn't think about was that I normally make the soldered connections under the Cerastil, which I could not do this way. All in all I think bare nichrome is best as it makes a much neater job. Here is the previous heater that I made way back in March :-



So after all these "improvements" how did the new extruder perform?



Not very well! I tried it with green ABS first but could not get it to extrude reliably. I swapped the nozzle for my previous 0.5mm brass one and that got it working.

I then switched to some plain ABS that I bought a while ago but have not been able to use because it is very oval. It was too wide for my previous extruder. This extruder has a 3.5mm bore so it should easily fit but I could not get it to work reliably. It takes an enormous force to push it into the extruder. I am not entirely sure why. If I pull it out and push some green in I can extrude the plain that is left in the barrel easily so it isn't any harder to push it through the nozzle but it is to push it into the heater.

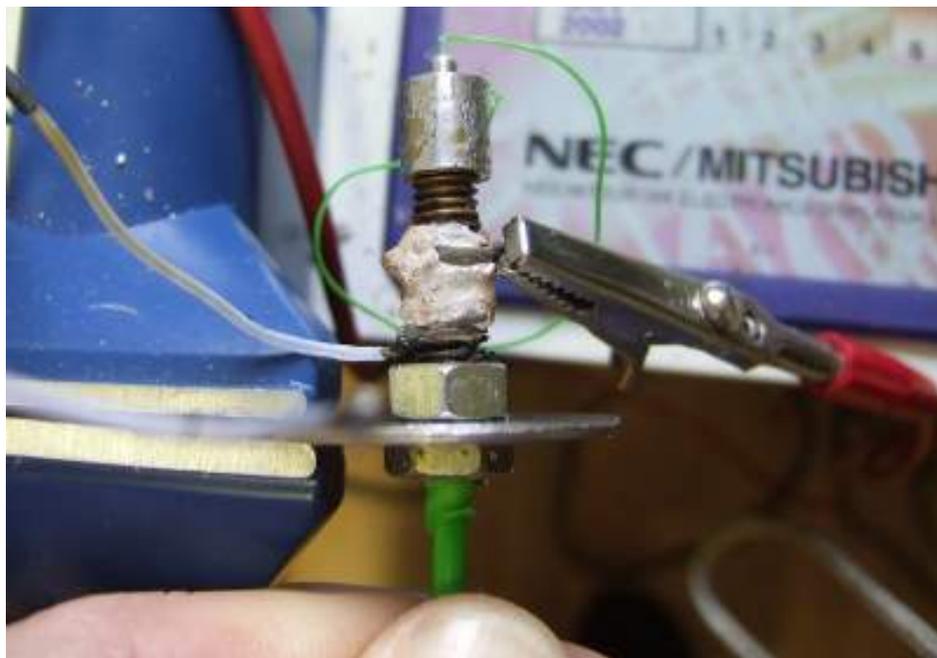
Since I foolishly changed every material at the same time it is hard to evaluate which things are better and which are worse. I have recently formed the opinion that the extruder design is far from optimum. I think we need a much sharper thermal gradient and a shorter heater barrel. I think a lot of force is wasted pushing slightly softened plastic down the thermal break.

My next attempt will have a very short thermal break with a heatsink at the cold side. I will also make it easier to strip down and reassemble. A problem with the current design is that once the heater barrel is screwed in and full of plastic it is hard to remove it.

# Simple experiment

Saturday, 27th December 2008 by Nophead

Inspired by Demented Chihuahua's extruder work, I repeated his experiment using what was left of my old heater. I mounted it in a 30mm M6 stainless steel washer and clamped that in a vice. I used my 0.3mm aluminium nozzle, which I counter bored with a 0.7mm drill to reduce the depth of the 0.3mm hole to about 1.5mm.



I powered the heater from a bench power supply and adjusted it manually to about the right temperature. Green ABS is handy for this because it changes colour at 260°C so you can tell when it is too hot.

I can extrude filament by pushing it by hand with moderate pressure. It comes out at 0.4mm but I should be able to stretch it back down to 0.3mm without any problems. Even with a 0.5mm nozzle I can stretch it down to 0.3mm, but I lose positional accuracy because the orifice no longer defines exactly where the plastic goes.

Originally the heater was 5mm longer, with the excess protruding beyond the half nut. I found that cutting that piece off made it easier to extrude. It was probably a relatively cool section so the plastic remained very viscous there.

When a new piece of filament is inserted into the heater it extrudes very easily. After a while some plastic flows backwards and builds at the entrance to the heater. That causes considerable extra resistance. I plan to tackle that by having a short section of PTFE at the entrance with a heatsink the other side of it. The steep gradient across the PTFE should freeze the back flow over a short distance and, being super slippery, should allow it to slide back into the heater.

Another thing I tried was forcing out the plastic using the shank of a 1/8" drill bit as a piston. The further the drill got to the end of the heater the less force was needed to push it. That confirms what I had suspected. The force to push the plastic through the long 3.5mm section of the barrel is very significant compared to the force to squeeze it through the short small hole in the nozzle. So the heater needs to be kept as short as possible. Obviously there will be a point where the extrusion rate becomes limited by the rate the plastic melts if it is too short, but I expect that is much shorter than the current set-up.

# Do we need nichrome?

Wednesday, 31st December 2008 by Nophead

While making a new heater I decided to try using stranded tinned copper tails rather than the solid tinned copper wire I used previously. The idea being to put less stress on the Cerastil covering.

I started with a standard piece of 7 x 0.2 stranded copper wire and removed the insulation. I found all seven strands too bulky so I decided to see how many strands I needed to carry 2A. I found that a single strand was cool to touch at 2A but very hot at 4A. I figured two strands would be sufficient for some margin.

The fact that a strand gets hot at 4A, and in fact red hot at about 5A, got me thinking that we could just use a single strand of copper for the heater. Nichrome is expensive, not that easy to obtain, and difficult to make connections to.

I measured the resistance of a strand 52cm long as about 0.3 (my meter only gives one digit). The strand measured 0.17mm diameter. Calculating its resistance from the resistivity of copper I get  $1.72 \times 10^{-8} \times 0.52 / (\pi (0.00017/2)^2) = 0.39$  .

At 4A the voltage drop was 2.6V giving a resistance of 0.65 and a power of 10W. The thermal coefficient of resistance is 0.0039 for copper so the calculated temperature of the wire is  $20 + (0.65/0.39 - 1) / 0.0039 = 191^\circ\text{C}$ . It was certainly hot enough to cut through ABS.

10W and 190°C are not far from the operating conditions of an extruder. I tried winding it on the bobbin I had made for my heater but it was about twice as long as I could accommodate. I am trying to make a very short heater at the moment so I went back to using nichrome. Also 2.6V @ 4A is too much for my current drive circuit but it would be easy to come up with a switch mode converter to drive it, or simply use the 3.3V rail of a PC PSU.

So it has definite possibilities. Making the connections would be trivial. Just start with a piece of 7 strand wire and cut it down to one apart from at the ends. Some high temperature solder would keep it neat but would not be essential. A standard heater barrel with some insulation would be about 7mm diameter so 24 turns would be required. If you keep it taught and wind it in a lathe or drill chuck you can get about 2 turns per mm with some concentration. That would easily fit the space currently allocated for the heater.

# New year, new extruder?

Sunday, 4th January 2009 by Nophead

The RepRap design has always aimed to be cheap and easy to make from readily available materials. What I desire though is good performance and reliability, and put those priorities ahead of the others. To me they are absolute requirements and the others are things to be optimised afterwards. With that in mind I set about trying to design a reliable extruder that I can make with the tools and materials I have available.

As it is experimental I wanted it to be modular so I can swap out things that don't work. I started with the heater. It takes me two days to make one so I wanted it to be removable and reusable. I made an aluminium bobbin with an M6 thread through the middle of it so it can be fitted to different barrel designs. The outside diameter is 12mm and the inner diameter is 8mm. It is also 12mm long. The flanges are 2mm and 3mm with a 7mm gap for the nichrome and Cerastil.



The surface is roughed up to make the Cerastil adhere well. It has a hole to accept the thermistor to make it a self contained closed loop.

I put down a layer of Cerastil about 0.5mm thick using a plastic jig and left it to cure over night.



I used two strands of 0.1mm nichrome in parallel to make the heater. That only needs 90mm to make about 6 . I normally use 8 but I anticipated more heat loss in this design.

To make connections to the heater I used two strands of 0.2mm tinned copper wire and attached them with reef knots.

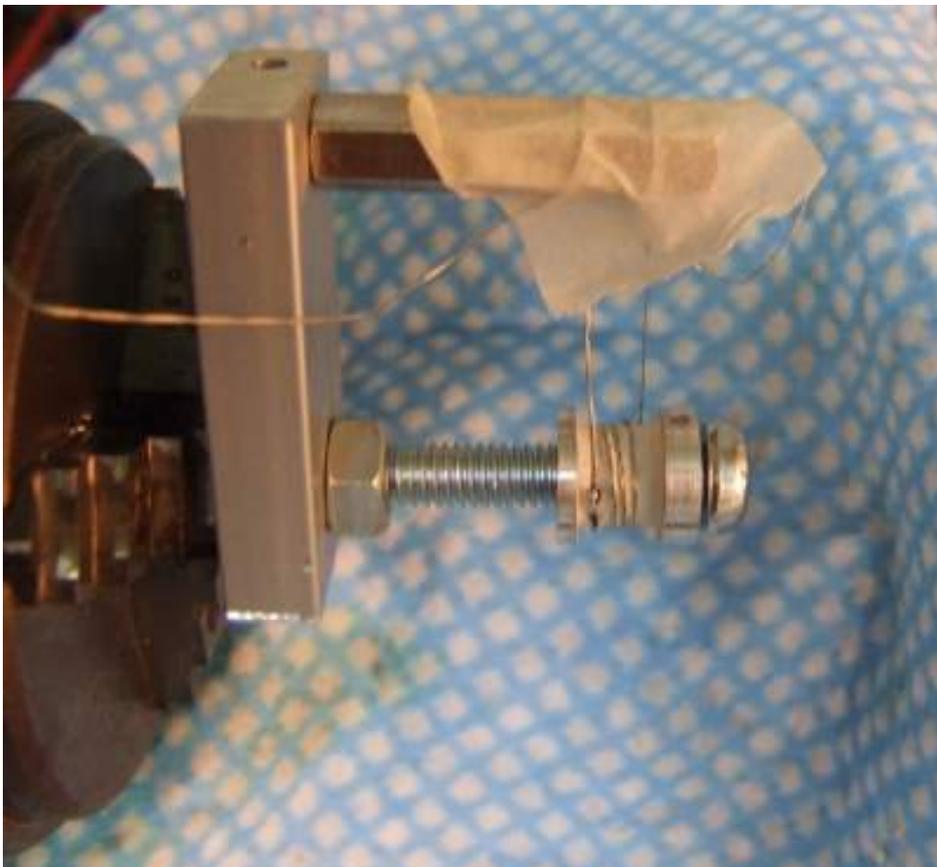


I then covered the knots in high melting point solder.



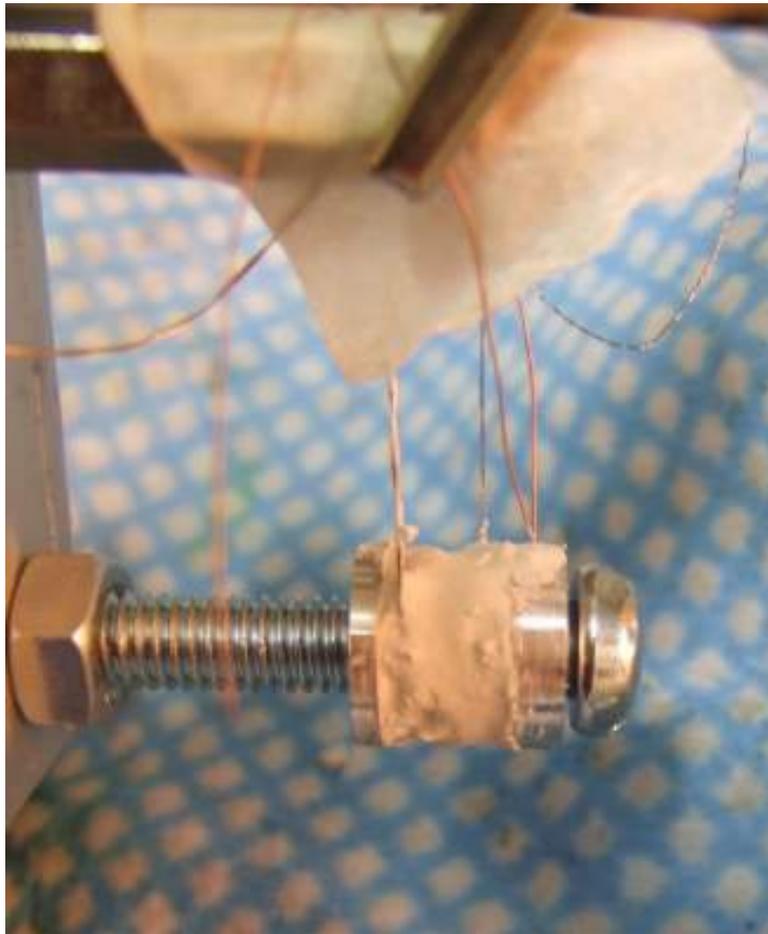
Using such fine copper wire may be a mistake as Bert pointed out on my previous post. Time will tell.

I made a jig to keep the wire taught while winding it on the bobbin.

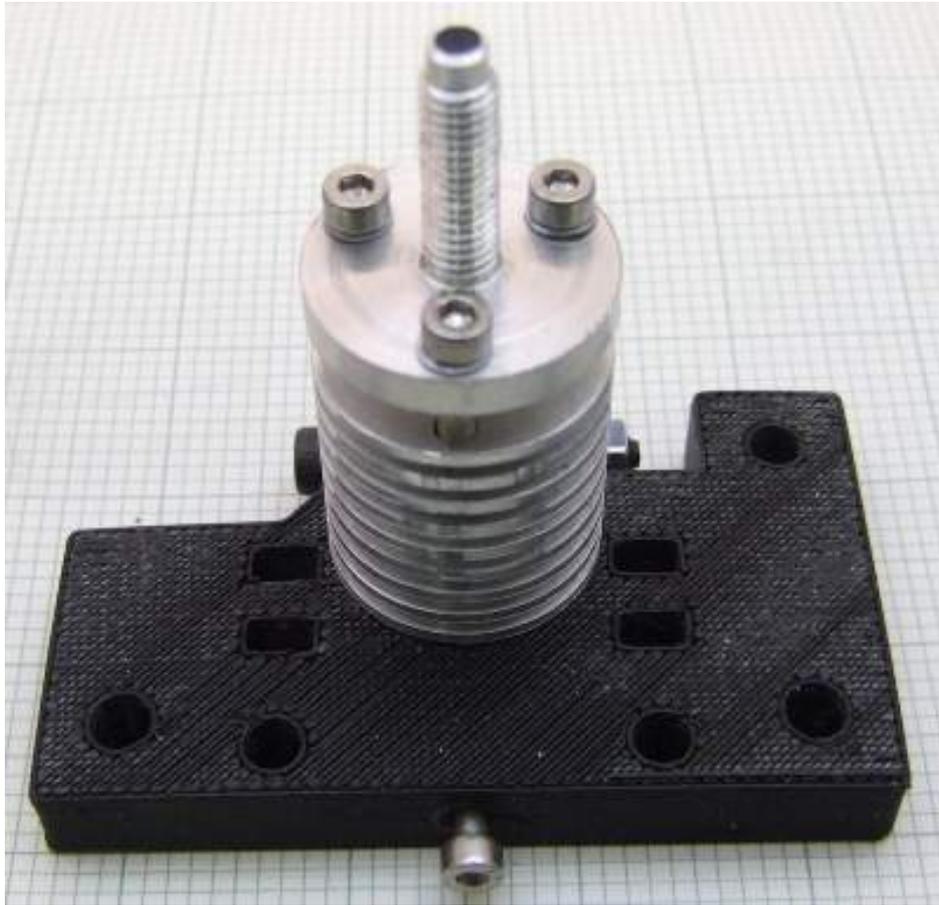


At this diameter it is only about three turns of nichrome.

Finally I covered the windings in Cerastil H-115 and also used it to glue in the thermistor.



I made the barrel as short as possible. That turned out to be 25mm to have room for the heater and the nozzle and a mounting flange. The standard design uses a 45mm heater barrel.



The vaned section is a heatsink to keep the rest of the filament path cool. Sandwiched between the hot and cold sections is a 12mm length of 10mm diameter PTFE tube.



The idea is to keep the thermal transition as short and slippery as possible to make it easy to push the slightly molten plastic through. The PTFE extends 5mm into the heatsink to give a good contact area for cooling. It extends 2mm into the hot barrel and 5mm is in the air gap. It is an interference fit and is under compression. When it gets hot and expands the seal should only get tighter.

The metal parts were drilled to 3.3mm on the lathe and once assembled it was all drilled out to 3.5mm. As the PTFE was drilled in situ the hole is perfectly aligned and there are no gaps.

The thermal loss through PTFE, which has a conductivity of 0.25 W/m°C, will be: -

$220 \cdot 0.25 \cdot \pi (0.005^2 - 0.00175^2) / 0.005 = 0.76W$ , assuming the heatsink is at 20°C and the barrel is at 240°C.

The barrel is held on by three M325 stainless steel bolts. The holes are counter bored so only the last 5mm of thread is in contact with the heatsink. Assuming the mean diameter of the thread is 2.75mm the heat loss through the bolts is: -

$3 \cdot 220 \cdot 17 \cdot \pi \cdot 0.001375^2 / 0.02 = 3.3W$

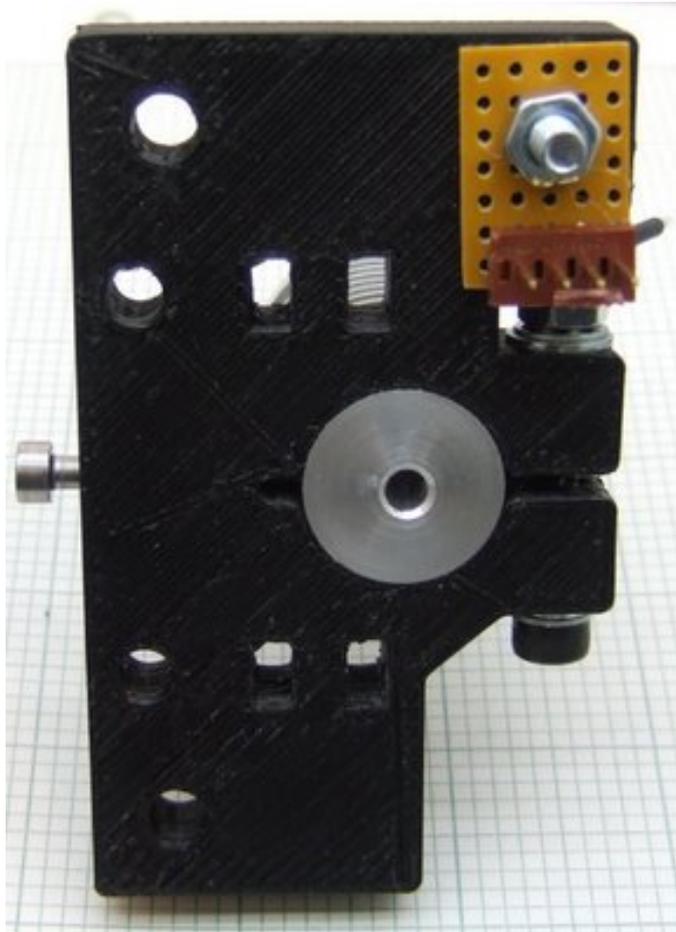
Longer bolts could reduce this by about half.

Here it is with the heater, nozzle and PTFE cover installed. There is heatsink compound between

the heater and the barrel, and the nozzle thread is sealed with PTFE tape.



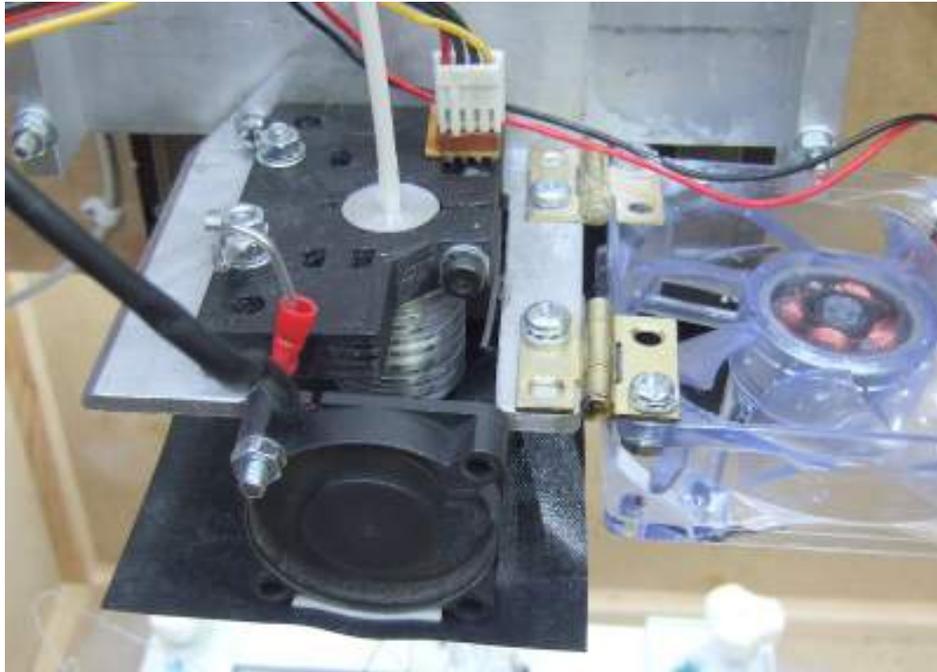
The wires are insulated with PTFE sleeving and terminated to a 0.1" header mounted on a scrap of Vero board. This mates with an old floppy drive power connector. I put the thermistor in the middle and the heater on the outer contacts so it doesn't matter which way round the connector goes.



The clamp seems to grip aluminium a lot better than it does PTFE but I also put an M3 bolt into a blind tapped hole to ensure it cannot slip. A good move as it turned out.

I powered it up without the pump and calibrated the thermistor. With the nozzle at 240°C the "cold" section reached 100°C and softened the ABS clamp. Obviously my home made heatsink is woefully inadequate.

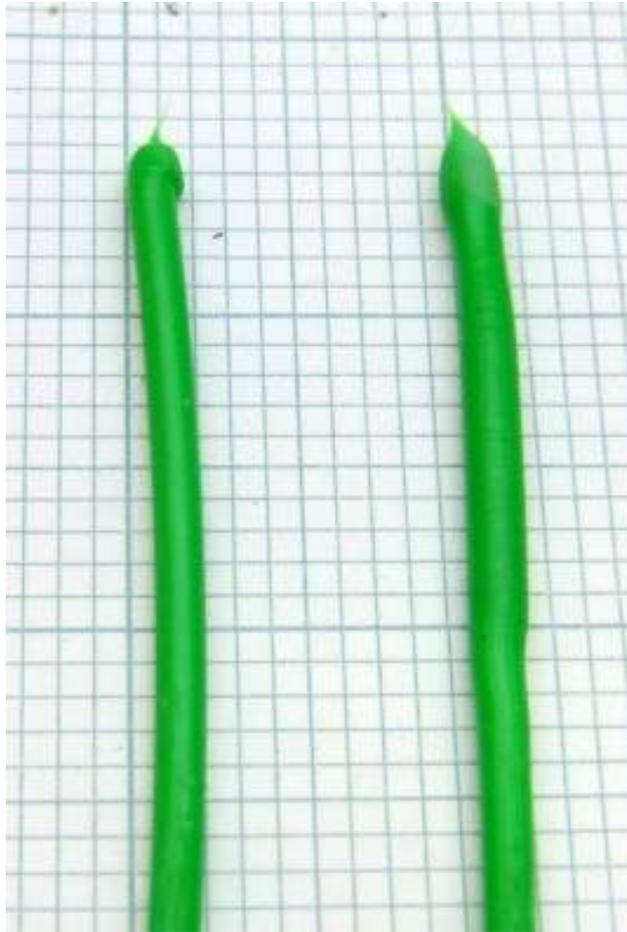
To keep it cool I added a small fan. That keeps the cold section at 30°C, much better.



The black sheet is Teflon baking parchment that I used to stop the fan blowing on the hot section.

I haven't attached the motor yet but I have tested hand feeding white, green and black ABS as well as HDPE. The ABS feeds easily through the 0.3mm nozzle and the HDPE with moderate force. I think they will all work well with the motor drive.

When the filament is pulled back out only a few millimetres has expanded at the end. In contrast, without the fan the filament swelled most of the way to the top and jammed. You can see the difference here: -



Keeping the melted section short is the key to making the filament easy to feed. The other improvement is that the PTFE is no longer a structural element. It is held in compression and appears to make a good seal with simply a push fit.

I am sure I can both improve the thermal separation and make it easier to make with a couple of design iterations before redesigning the other half of the extruder.

# Heater in a hurry hack

Friday, 9th January 2009 by Nophead

The heater in my last design has two layers of Cerastil that take 24 hours each to cure and the bobbin takes some time to machine. Attaching the wires and winding the coil is quite fiddly. Looking for a short cut I wondered if we could use power resistors. I had this one lying around to play with.



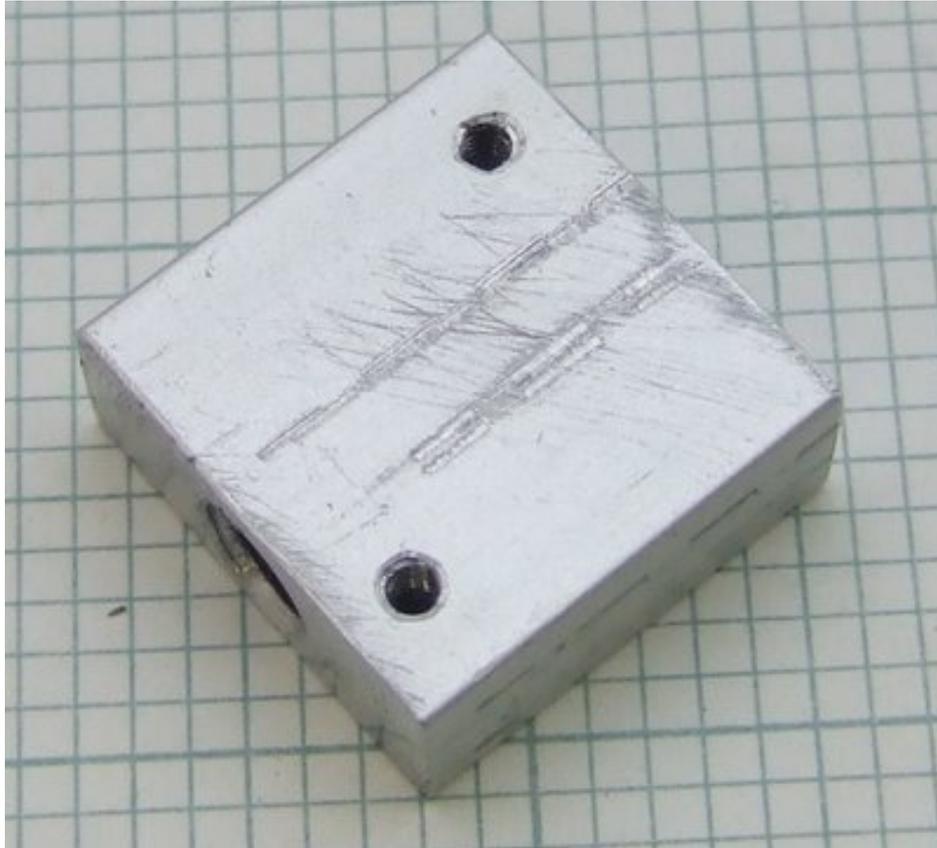
Unfortunately it is only rated for operation up to 200°C. In fact the datasheet says "It is essential that the maximum hot spot temperature of 220°C is not exceeded". Curious to see why, I put enough voltage across it to heat it up to 240°C. That turned out to be about 75W. It seemed quite happy at that temperature for several hours.

It is too big really for an extruder so I bought some smaller 10 Watt ones for £1.42 each.

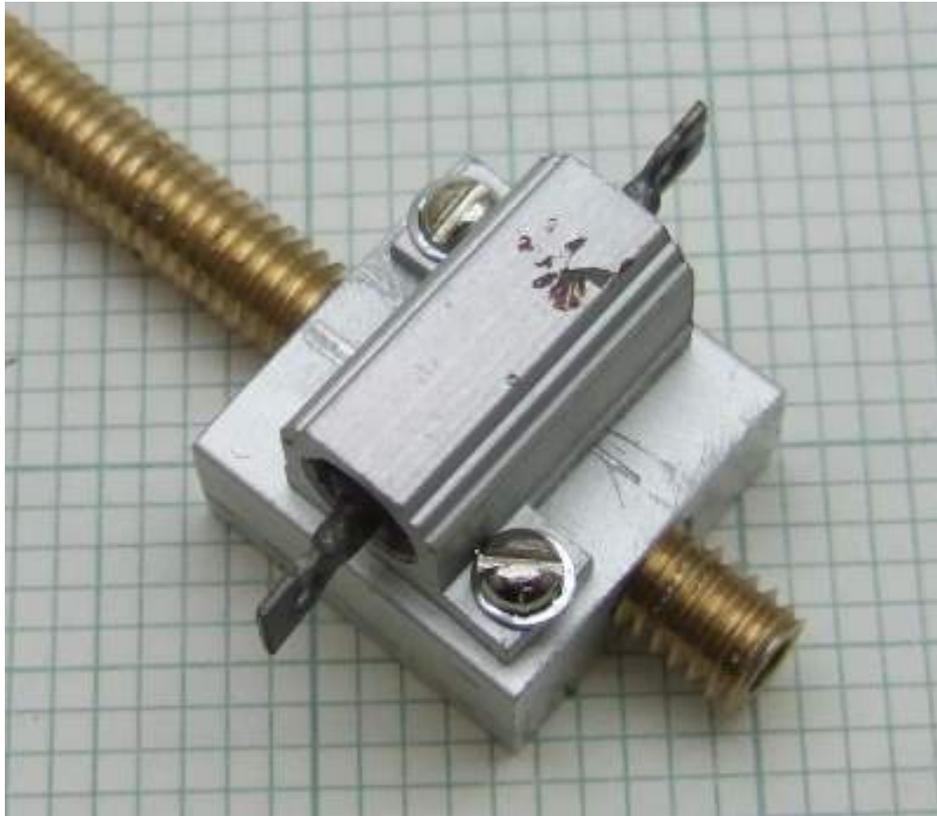


These are only rated for 165°C but what the heck. I heated a 6.8  $\Omega$  one to 300°C. At about 180°C it produces a little smoke but that soon goes. At 280°C it starts to smell bad, but at 240°C it seems happy. I left one powered up for a few days. The writing disappears and the connection tags oxidise, but its resistance is stable.

To make a heater I cut a 19mm x 19mm x 8mm block of aluminium from a bar, drilled a 5mm hole through it and tapped it to M6 to fit a heater barrel. The mounting holes of the resistor are big enough for M2.5 but there is not enough room for the head, or a nut. M2 is a bit weedy so instead I used 8BA bolts. These need a 2.8mm hole for tapping. A simpler solution would be to just file a flat on the head of an M2.5 bolt, drill a clearance hole and use a nut on the other side.



Here is the full assembly: -



I put heatsink compound on the M6 thread and under the resistor. I attached tinned copper wires with 300°C solder and insulated them with PTFE sleeving.

I have run the assembly for a couple of days and it held up. I am loath to recommend something which is unsound engineering, but it does seem a simple and robust solution as long it lasts a reasonable amount of time, say 1000 hours. Replacement is easy because the most time consuming thing is making the block which is reusable. I expect there might be some matching crimp connections to avoid the high temperature solder.

Quite a lot of heat is lost from the large surface area so some insulation would be a good idea.

# Thermal gradients

Sunday, 11th January 2009 by Nophead

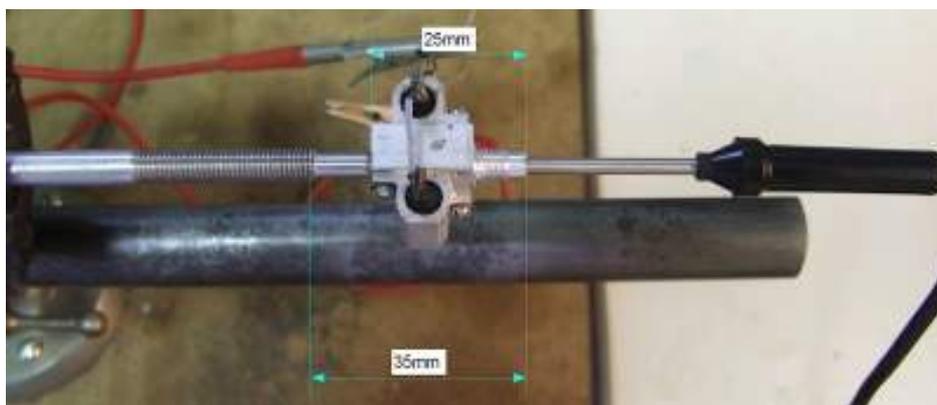
Although my last extruder design seems to work, I am not very happy with it. I don't like the little fan because it is noisy, it isn't easy to make and it is not very thermally efficient. The main heat loss is via the stainless steel bolts and from the big flange. The only reason those parts are needed is because the PTFE insulator does not have the necessary mechanical strength and stability.

Some time ago I tried to use stainless steel as the insulator because it is strong, self supporting and withstands high temperatures. That attempt failed because my thermal gradient was too long; the hot to cold transition was about 50mm. The extruder would run for a while but would always jam before an object was completed. Once the stainless steel barrel was fully up to temperature the amount of filament that is soft but not fluid is sufficient to provide too much resistance to be pushed. This theory was confirmed when I tried a soldering iron heater, which also has a long thermal gradient along its length.

I also tried PEEK as the metalab guys had success with it but that seemed to suffer from the same problem.

I had always intended to revisit the stainless steel idea with a shorter transition zone but when I saw Larry Pfeffer's stainless steel extruder it provided an extra idea of thinning down the pipe at the transition. That allows a short transition without too much heat loss or loss of mechanical strength.

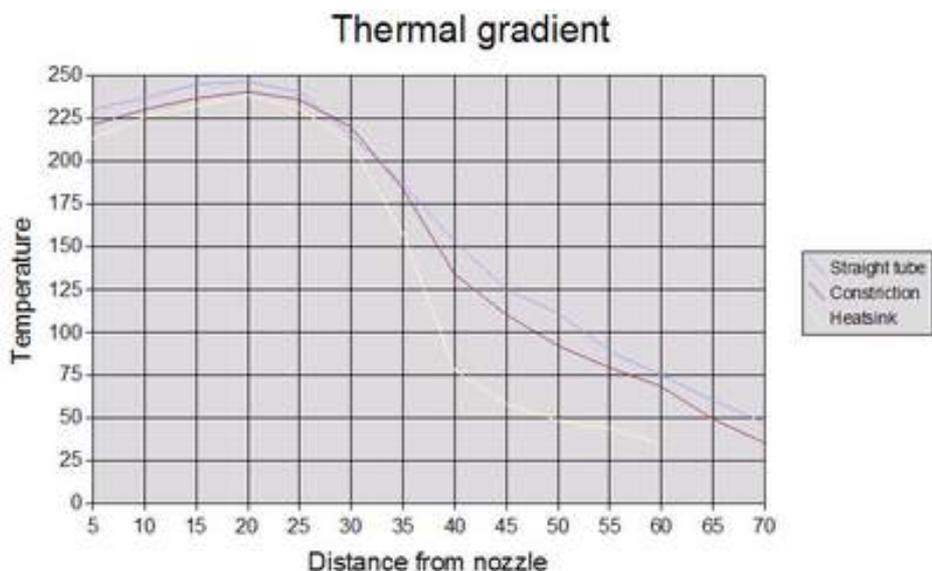
I did some experimentation with this test set-up.



I made a heater with an integral aluminium barrel by turning some aluminium bar in my four jaw chuck, the first time I have used it. I used two 12 resistors in parallel this time instead of one 6.8 . They give a bit more power and possibly lower internal temperature inside the resistors.

I measured the temperature along the tube at 5mm intervals. The thermocouple is slightly smaller than the internal diameter of the tube. The weight of its cable causes the tip to rest on the roof of the tube and the other end rests on the floor of the filament exit. The thermocouple is itself encased in stainless steel, so there will be some heat leaked along it. Hopefully its casing is thin enough to have little effect compared to the much thicker tube it is sampling.

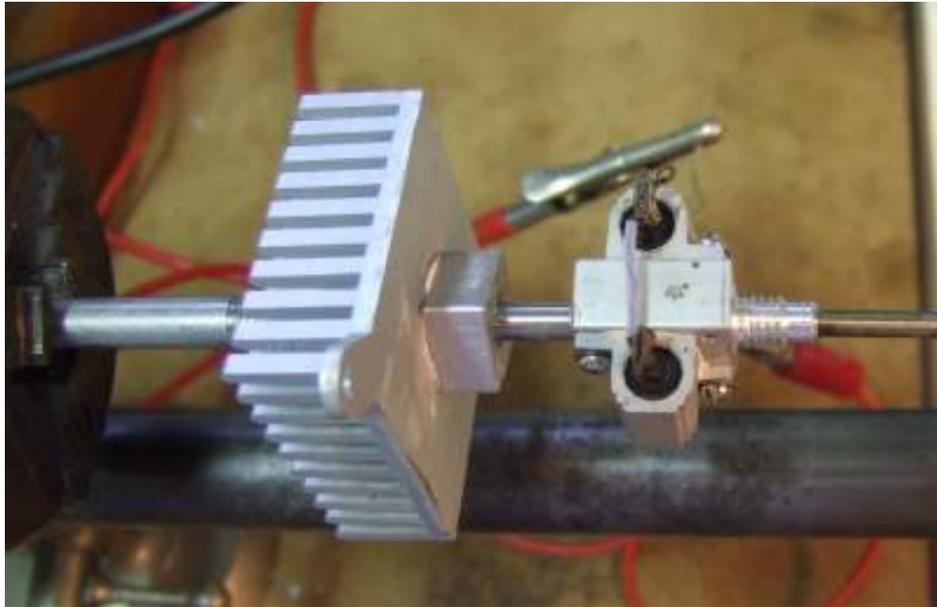
The heater was powered from a bench power supply and the voltage adjusted manually to give around 240°C in the middle of the heater block. That needed 9.4V which is 14W. I can feel substantial heat rising from it so some insulation would make it a lot more efficient. I have got some ceramic fibre kiln insulation for that, another tip I picked up from Larry's blog.



The first test was with a threaded tube with no constriction. The gradient is not far from linear, it falls off faster when hotter due to more convection and radiation from the hot section. If we assume ABS would be soft but very viscous between say 75°C and 125°C we see that it covers 45 to 60 i.e. 15mm.

I then turned a 10mm section of the tube down from 6.4mm to 4.5mm. The internal diameter of the tube is about 3.6mm so that gives a wall thickness of 0.45mm. That made the gradient steeper between 35mm and 40mm but the length of the perceived problem zone gets bigger. I am not sure how Larry gets away without a heatsink. I think he is using thicker pipe so there is a much bigger difference between the conduction of the constricted section and the rest. Also it takes a long time for the problem to become apparent because heat travels slowly down the pipe.

The final test was done with a heatsink attached just above the constriction. The centre of the heatsink only reached about 28°C. The aluminium block I used to connect it got hotter but was still comfortable to touch so less than 50°C.



The gradient between 30mm and 40mm is now much steeper. Odd that it is not between 25mm and 35mm where the constriction is. Almost like there is a 5mm offset in the readings. Anyway the 125°C to 75°C transition is now only about 3mm.

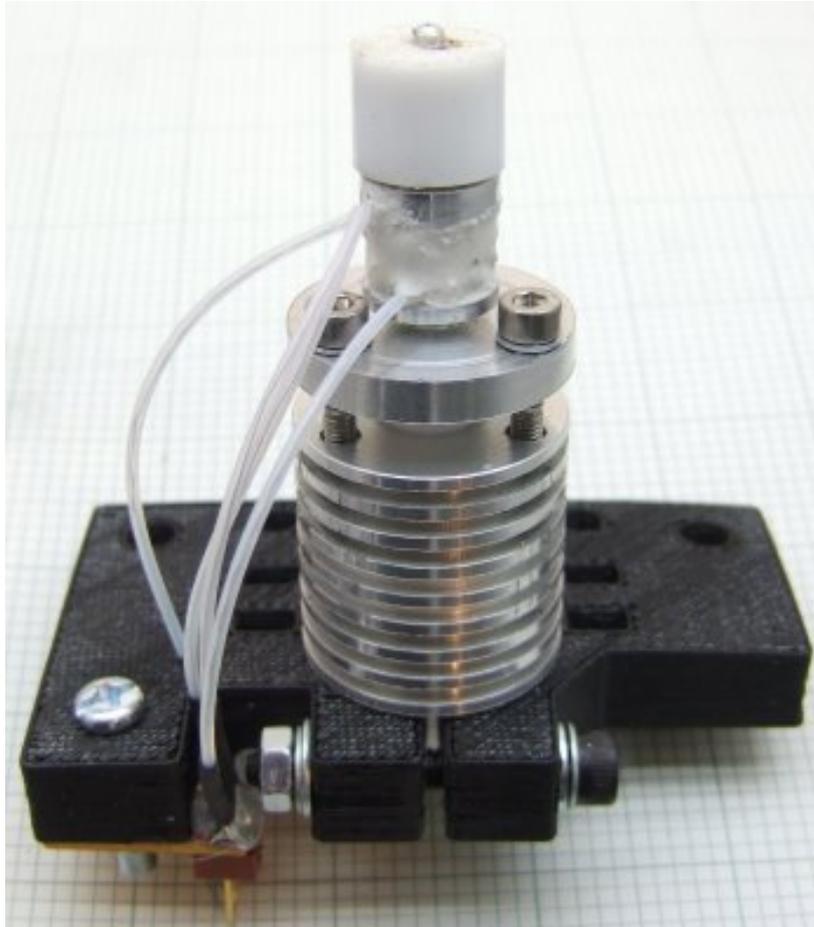
If we assume the temperature difference across the constriction is 210°C - 80°C = 130°C, the conducted heat loss is temperature difference thermal conductivity cross sectional area / length. So  $130 \cdot 17 \cdot \pi \cdot ((2.25 \cdot 10^{-3})^2 - (1.81 \cdot 10^{-3})^2) / 10 \cdot 10^{-3} = \sim 1.3W$ , about 1/3 of the loss through the bolts and PTFE in my previous design.

So it looks promising, I need to add a nozzle and some insulation and see if it will extrude.

# Fanless

Saturday, 17th January 2009 by Nophead

I have not succeeded yet in getting the stainless steel barrel to extrude easily, so I had a go at improving my aluminium extruder to remove the need for a fan.



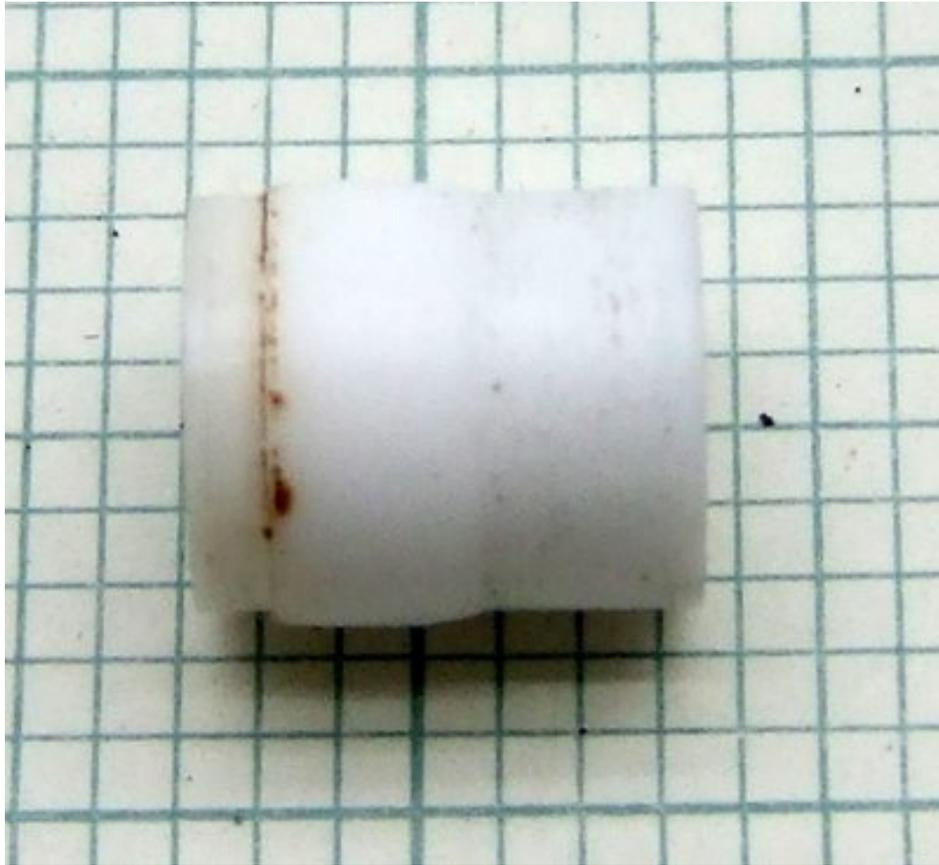
A lot of heat is lost from the large flange on the top of the heater barrel and transfers by convection to the heatsink above and by conduction through the bolts.



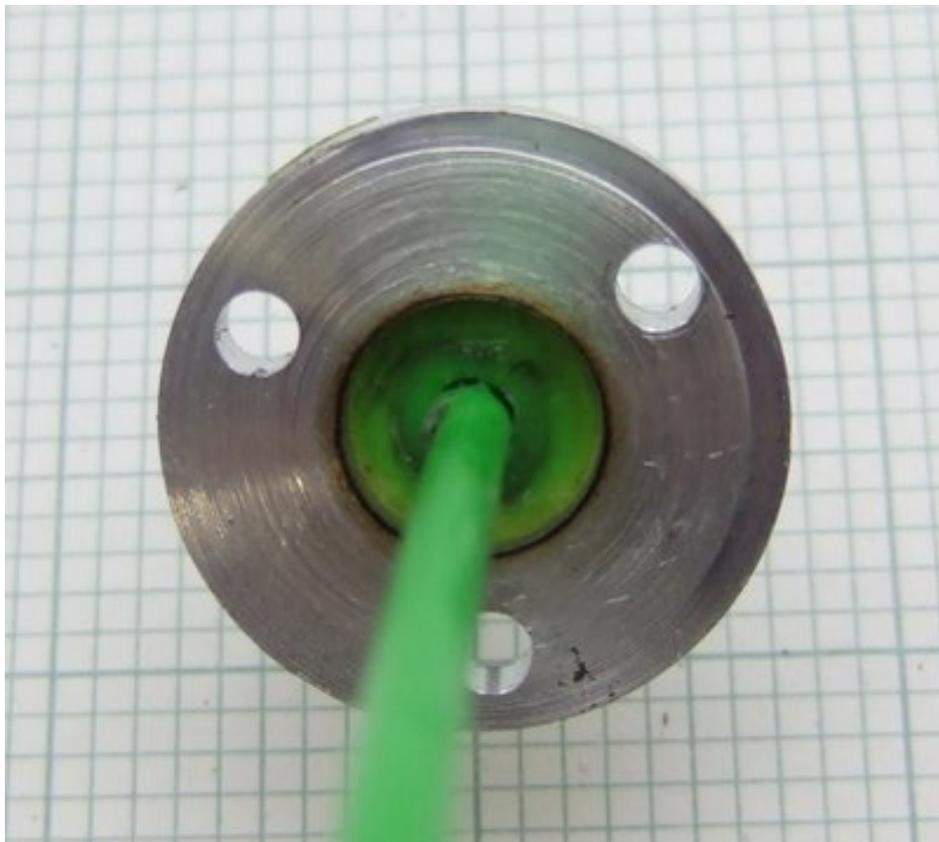
When I stripped it down I noticed the bolts had loosened.



The PTFE had shrunk lengthways and expanded in diameter and was no longer making a good compression seal.



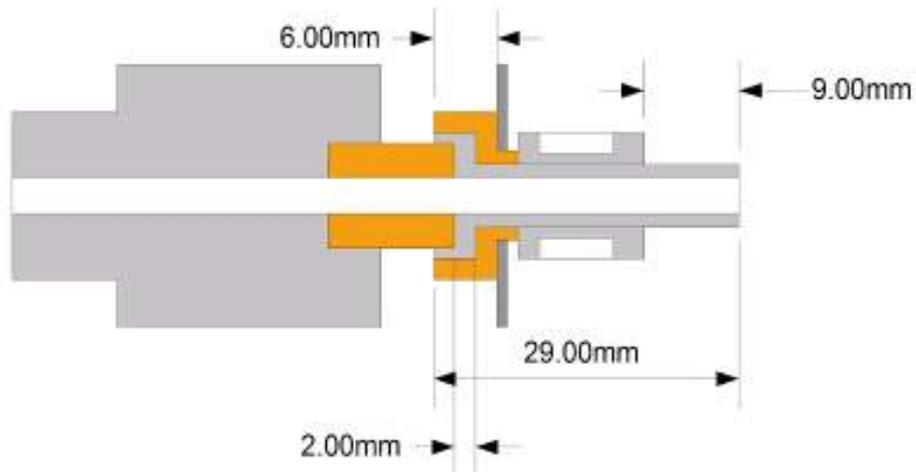
Although no plastic had escaped it had leaked under the PTFE.



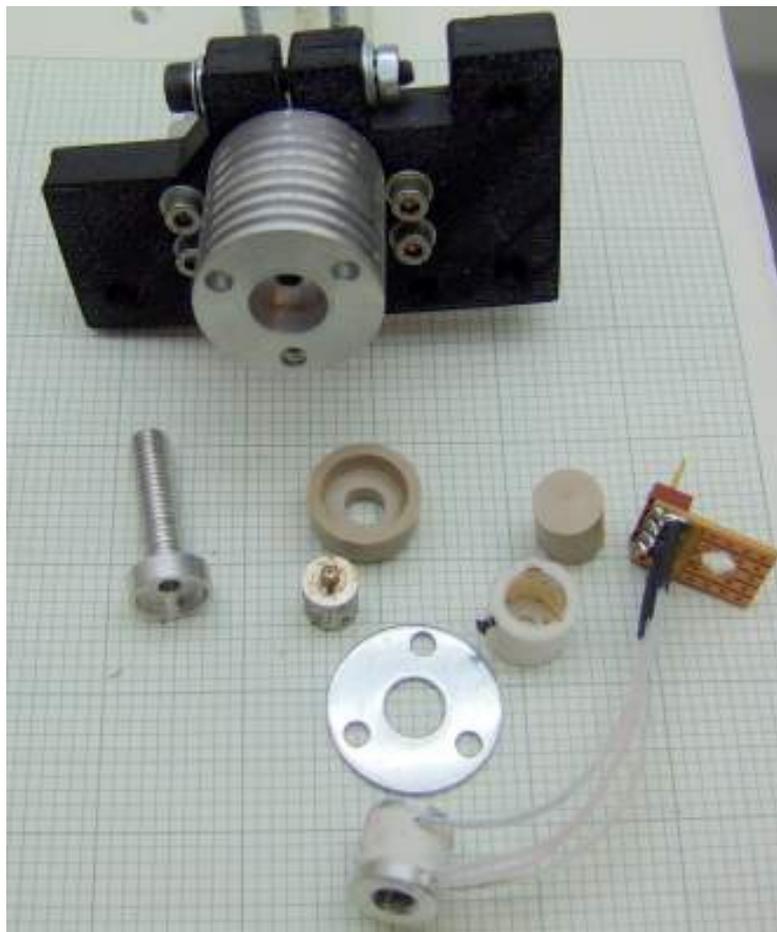
I think it was leaking so slowly that it oxidized where it met the air and went hard, stopping further flow. I hadn't run it very long so it may have escaped eventually.

So PTFE is obviously no good in compression at these temperatures. I replaced it with PEEK, which is a shame because it is about ten times more expensive.

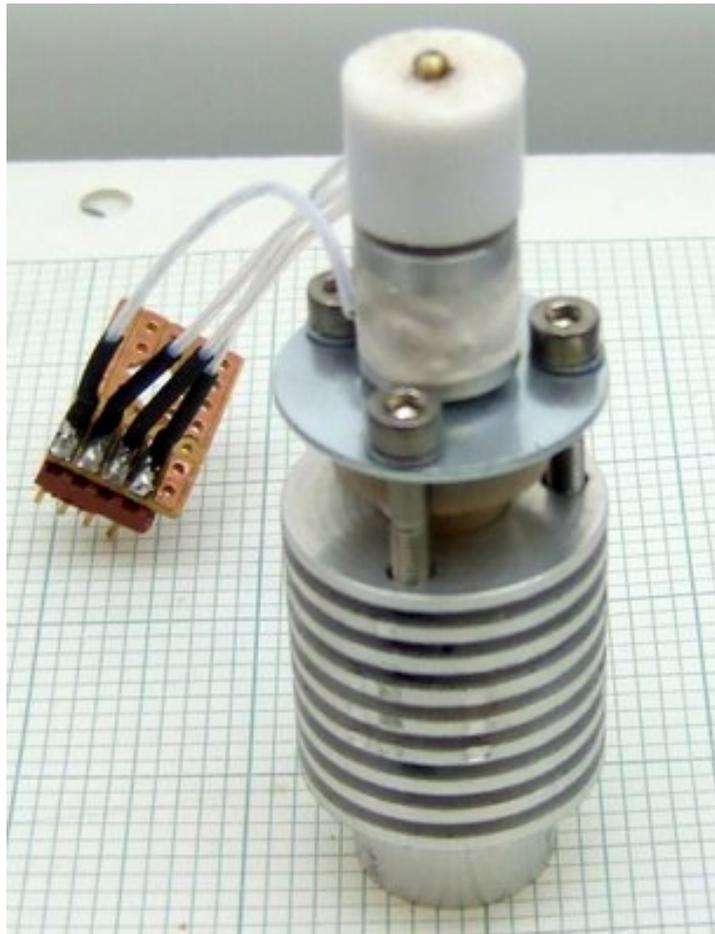
I also replaced the aluminium flange with an M8 x 25mm steel washer insulated from the barrel by a PEEK collar.



Here are the parts, the PEEK section is drilled in situ to get perfect alignment: -

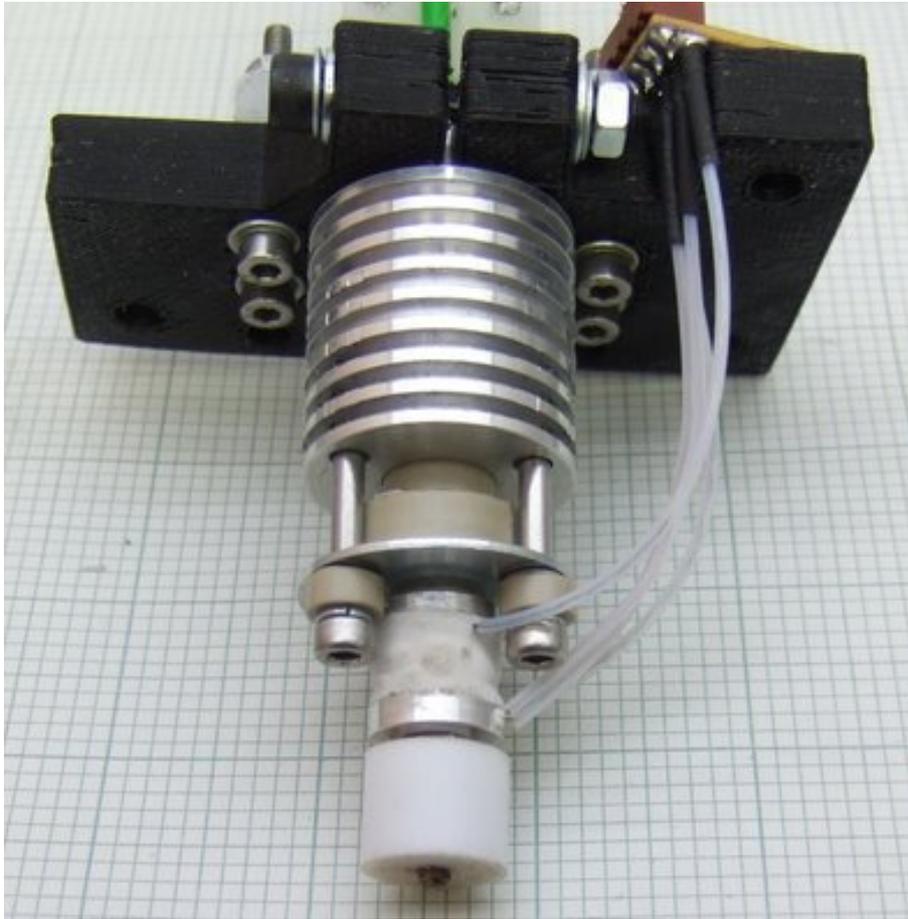


And here it is assembled: -



I put some PTFE plumbing tape over the hot end of the PEEK before pushing it into the aluminium in an attempt to improve the seal.

The heatsink now runs at 80°C without the fan. I would have liked it to be lower but as long as it is below the glass transition of the filament and the clamp it should be OK. I tried insulating the bolts with PEEK washers but that only dropped the temperature by 5°C, so not really worth the effort.



After one heat cycle I noticed the bolts were not as tight as they should be so it looks like PEEK creeps a bit as well. Perhaps glass filled would be better.

It is disappointingly complex with lots of machined parts but it does work very well. The heater power has dropped to 50% from about 80-90% with the fan. ABS filament extrudes manually very easily and even HDPE only requires moderate force. I think actually having the long heatsink preheating the filament to just below the glass transition is probably a benefit.

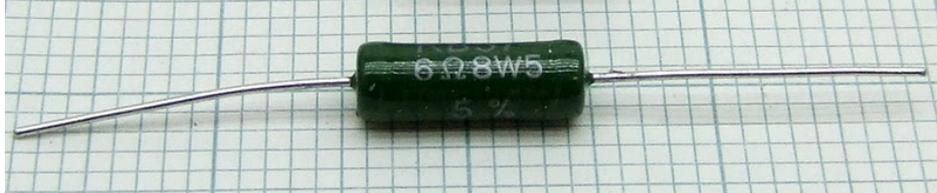
It is too early to say whether this design will be reliable but other than the PEEK section leaking there isn't anything likely to fail. I don't mind making things that are difficult to make provided I only have to do it once.

I also have a much simpler design in mind that should achieve the same short transition zone.

# Yet another quick heater hack

Saturday, 17th January 2009 by Nophead

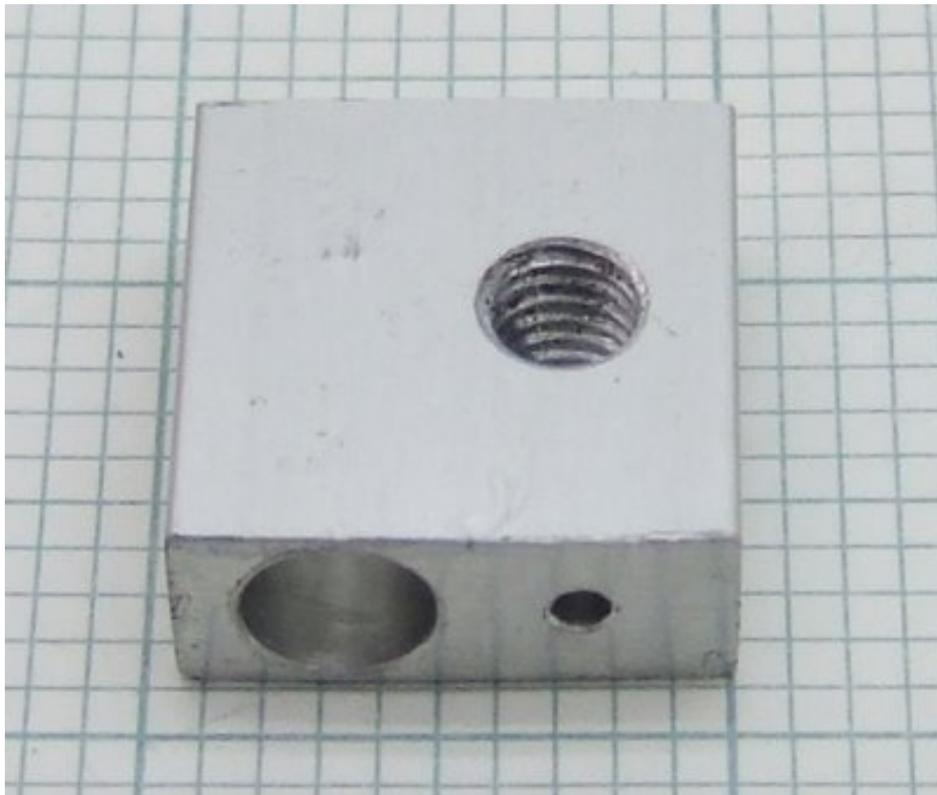
The ideal off the shelf heater would be a cartridge heater but they tend to be at least 1" long, need mains voltage and are very expensive. Here is a cheap 12V alternative: -



It is a vitreous enamel wire wound resistor that can handle surface temperatures up to 450°C. It is a 6.8 RWM 6 x 22 rated at 10W, but I am overloading it somewhat to get 240°C.

I bought a pack of five from RS. Farnell and Newark also stock them I believe.

I drilled a hole to accept it in a 19 x 19 x 8mm block of aluminium with an M6 tapped hole for the heater barrel and a small hole for a thermistor.

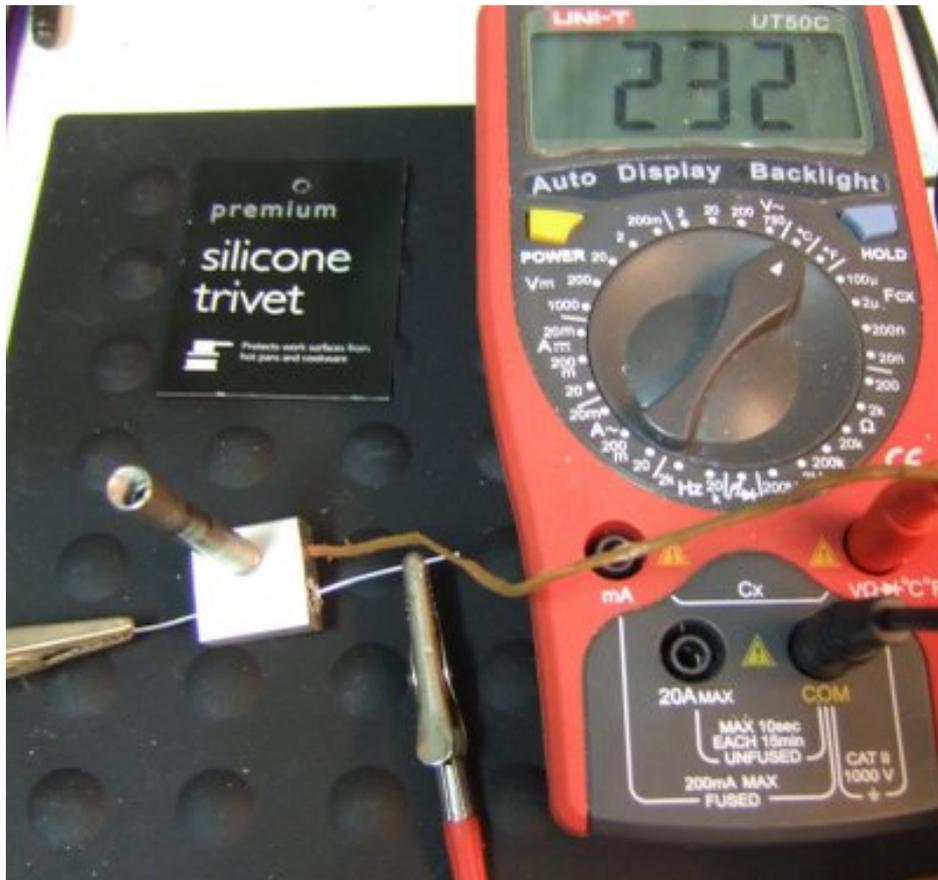


The tapped hole is at right angles so that the hot zone is as short as possible. It could be made parallel to get more contact area.

The outside diameter of the resistor measured 6.3mm so I drilled a 1/4" hole for it. That was too

tight so I drilled it out to 6.5mm. I then wrapped aluminium kitchen foil around the resistor to make it a tight fit and rammed it in.

Here it is under test with a random bit of tube to simulate a heater barrel.



It needs about 11W (8.7V) to get to 240°C. 14.7W (10V) gives 300 °C. I haven't run it for very long so no guarantees it will last, but I can't see why not.

Compared to the aluminium clad resistors I tried before, these are cheaper and you get a more compact heater with a smaller surface area to lose heat from. Also making connections should be no problem with normal solder because the wires are long enough to cool down.

# HydraRaptor's New Year's Resolution

Saturday, 24th January 2009 by Nophead

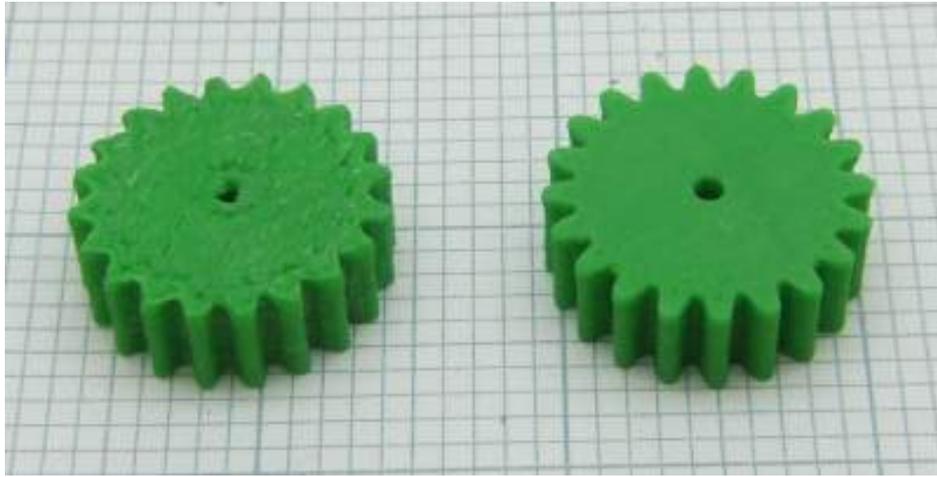
My new extruder has a 0.3mm nozzle compared to 0.5mm that I have used before. The actual filament diameter is controlled by the flow rate versus the head feed rate, so a single nozzle can give a range of filament diameters.

The maximum diameter is governed by the hole size and the die swell. The head movement has to be about the same as the rate that the filament leaves the nozzle, or faster, otherwise the filament squirms about and makes a zigzag instead of a straight line. Fortunately the faster the flow rate, the more die swell there is, which works in our favour when trying to extrude the maximum diameter filament. With the 0.5mm nozzle I could extrude up to about 1mm with ABS and I used that to good effect when making the first layer of the raft. With a 0.3mm hole die swell is more but even so I can only get 0.8mm filament. That makes the first raft layer thinner, so it is less tolerant to the bed being uneven.

I normally extrude at a rate that produces filament the same diameter as the nozzle but it can be stretched further making it smaller than the nozzle. The limiting factor is when the filament starts to snap. I did make some 0.3mm filament with the 0.5mm nozzle but I don't think I got the full benefit of the extra resolution because the filament was less constrained as the nozzle changed direction.



These two gears are both made from the same gcode with 0.3mm filament giving a layer height of 0.24mm. The one on the left was made with a 0.5mm nozzle and the one on the right with the new extruder with 0.3mm nozzle. The latter is slightly better defined. The benefit is more apparent on the underside.



The bottom of the one on the left feels perfectly smooth due to being made on a raft with a very fine surface. It is actually smoother than a sample I have from a commercial machine.

I was disappointed that it did not improve the clockwise slant of the teeth. This must be due to the same effect that makes holes come out too small. The filament likes to cut corners, so when the head moves on a curved path the filament takes a smaller radius path. I noticed that the teeth are straight at the base but slanted at the top, so the effect is somewhat cumulative.

I made another one with the outlines anti-clockwise on every second layer. Here is a video of it being made: -

[HydraRaptor RepRapping a gear from Nop Head on Vimeo.](#)

The teeth came out straighter but the edges are slightly more ridged because each layer alternates a little.



The surface is not quite as good as the previous one. I put that down to variations in the feed stock diameter. You need exactly the right amount of plastic to get a good surface.

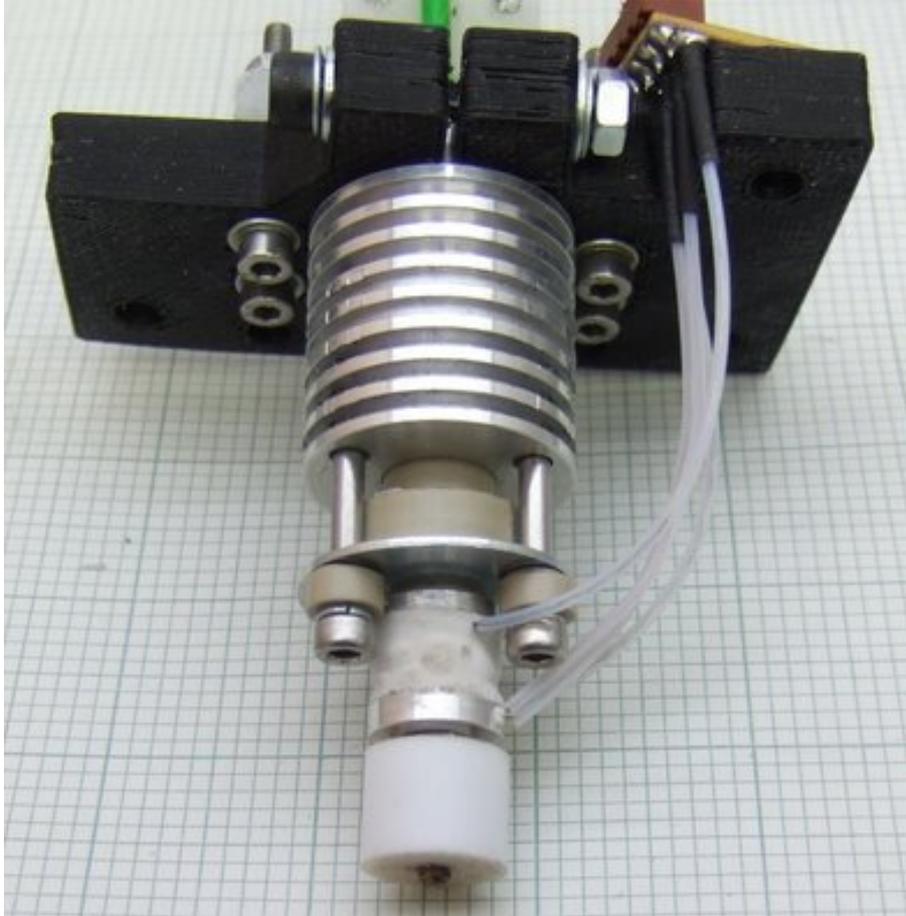
I also need to up the resolution of my z-axis. 0.05mm is significant with 0.24 mm layers, so I will have to add microstepping like my other axes.

So in summary 0.3mm nozzle gives noticeably better results and can still make 0.5mm filament due to die swell. It is harder to get the raft heights and temperatures correct. To get the same build rate with 0.3mm filament I would have to extrude at 44mm/s, but HydraRaptor is currently limited to 32mm/s. I could probably tune it up to 44 but the vibration gets a bit ridiculous as the moving mass of the table is 9Kg.

# Evolving extruder

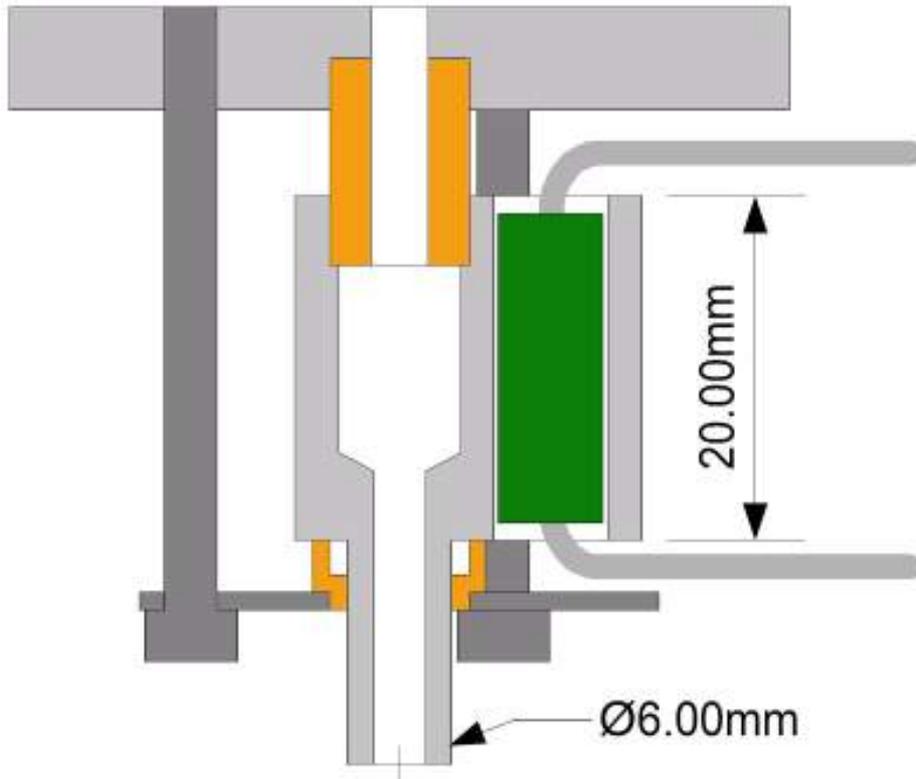
Monday, 2nd February 2009 by Nophead

The fanless version of my new year extruder works well but is not the easiest thing to make.

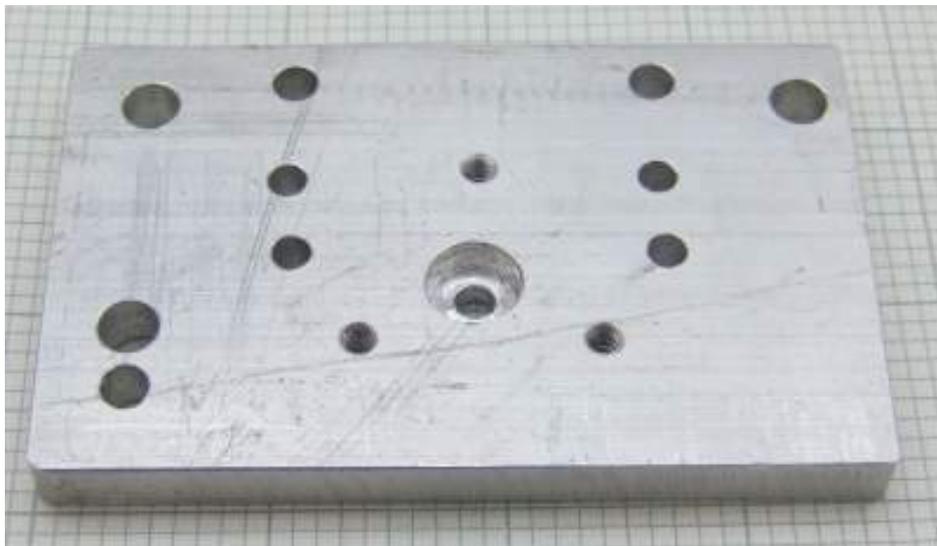


I have redesigned the lower half to be a lot simpler. I also wanted to see what would happen if I made a cavity of molten plastic inside the heater. Up till now I have been trying to minimise the amount of molten plastic to reduce ooze, but according to Anon's comments here, professional machines have a relatively large melt chamber. I wondered if plunging the filament into a chamber of already molten plastic would make it any easier to feed.

This is a cross section of my design: -



The plastic clamp and cylindrical finned heatsink have been replaced by a single horizontal 6mm thick aluminium plate that combines both roles.



The easiest and most accurate way to have made this would have been to mill it with HydraRaptor. If I make another, that will be the way I do it, but I made this one with a hack saw, a file and a drill press. I start by gluing a paper template on the aluminium with stencil mount.



I then centre punch through the cross hairs and drill all the holes. The paper can be removed easily by dissolving the spray mount with paraffin. The larger mounting holes fit the Darwin X-carriage and the smaller ones fit HydraRaptor. The group of four holes allow the standard filament guide to be attached. The Darwin extruder clamp has slots but slightly oversized holes are fine.

The 8mm counter bore was a bit tricky. I drilled it with an 8mm drill and then bottomed it with an 8mm end mill. That showed that my drill press / mill is not really stiff enough to mill aluminium with an 8mm bit even though it has a 45mm thick steel pillar. I don't think HydraRaptor would have any problem doing it slowly with a small end mill. It probably doesn't make much difference if the counter bore does not have a flat bottom, so simply drilling would suffice.

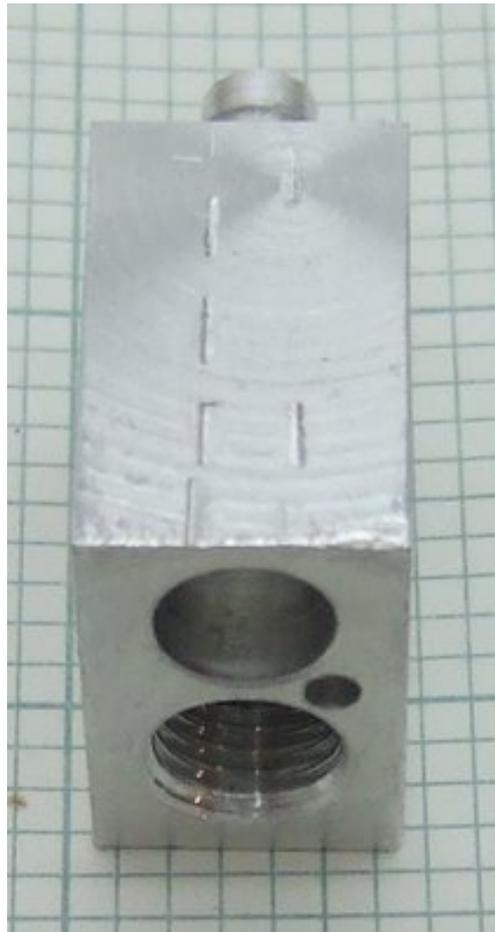
Moving down the design is the PEEK insulator that forms the short thermal transition zone.

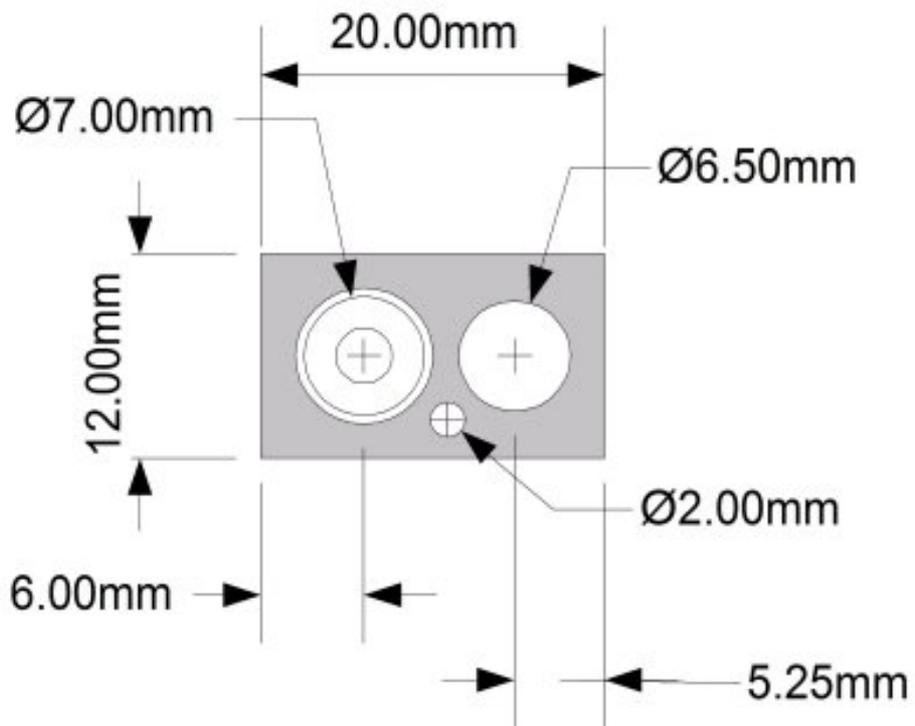


This is 8mm PEEK rod tapped with an M8 x 1 thread so it can screw into the heater block. I used the metric fine pitch because I didn't have the correct tap drill for M8 x 1.25 (6.75mm). The 3.5mm hole down the middle is drilled in-situ to ensure it lines up with the hole through the heatsink.

Small diameter PEEK rods are far more reasonably priced: 250mm x 8mm is only £3 here and is enough to make about 20.

The heater is a block of aluminium with a 6.5mm hole through it to take a vitreous enamel resistor for the heating element as described before.





As well as the tapped entrance to the melt chamber there is a small hole to take the thermistor.

I made this on my lathe, using a four jaw chuck. It could however be made with a drill press if the nozzle screwed into it instead of it screwing into the nozzle. The lathe gets all the faces perfectly

square but there is no reason why it has to be accurate.

The next part down is a PEEK collar to insulate the heater from its retaining washer.

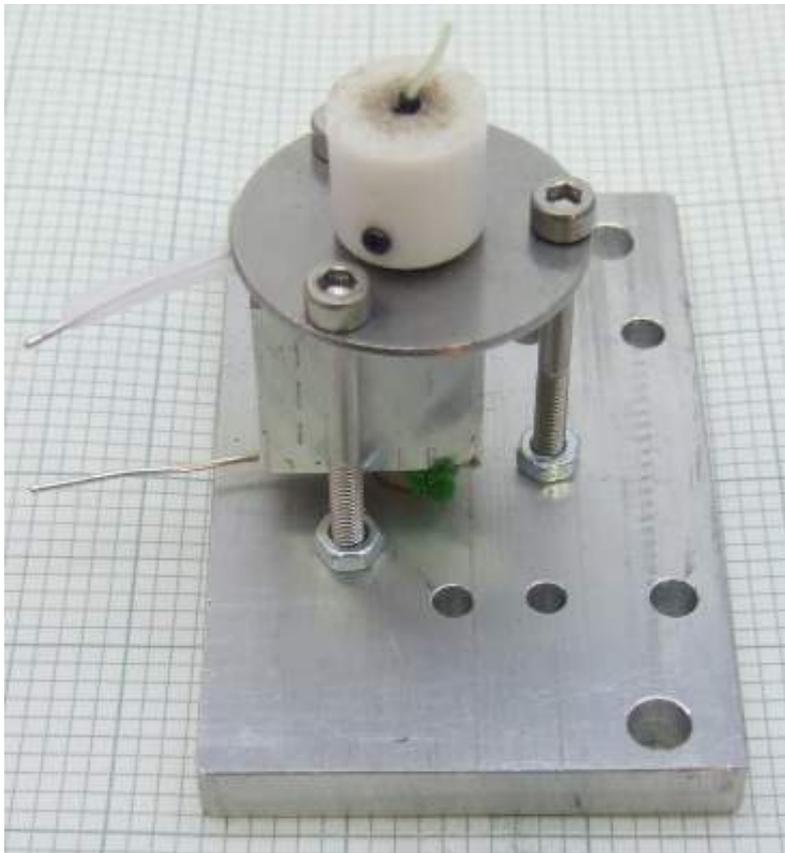


This is the only part I haven't thought of a way to make without a lathe. It might be possible to mill it with the right shaped cutter.

It snaps into the stainless steel washer and is a tight fit to the M6 spout so it anchors the nozzle laterally as well as vertically. It is counter bored at the back to reduce the thermal coupling.



Here is the assembly: -



It leaked a little bit of ABS but it seemed to stop when the leaked ABS oxidised. I should have sealed the joint with PTFE plumbers tape as I normally do. Apart from that it seems to work very well. I was able to manually push ABS through a 0.5mm nozzle very easily, at great speed. HDPE extrudes pretty quickly as well. When I stop pushing, it stops pretty quick. I think with a reversible drive ooze should be OK.

The design is much shorter than the previous one which will increase the build volume on Darwin. It is also very rigid so will not deflect when extruding.

I intend to simplify construction further. Rather than drill the stainless steel washer I can use the technique Ian Adkins uses on the BfB extruder where it is trapped between nuts and washers on studding. The only reason I did it this way was because I had the stainless steel bolts but did not have any M3 stainless studding.

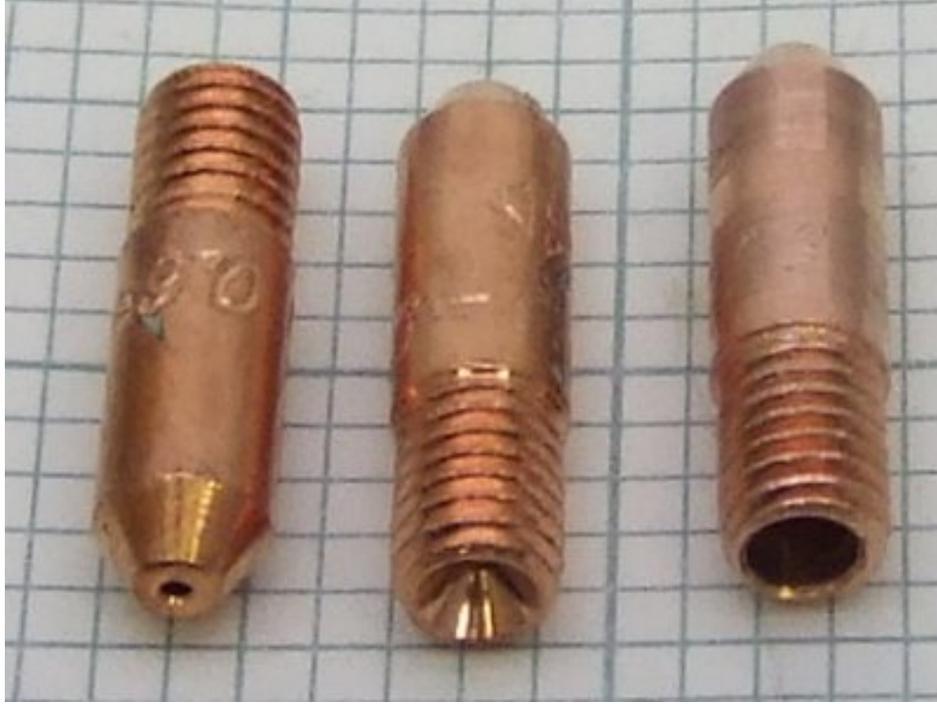
I will also look at screw in nozzles. Andy Hall uses copper welding tips. The exit hole is a bit on the large size but I can reduce it by blocking it with high temperature solder and then drilling that, as I did with the solder sucker bit I tried.

The next task is to make a reliable drive mechanism to go on top.

## Top tip

Wednesday, 4th February 2009 by Nophead

I got the tip to use welding tips for an extruder nozzle from Andy. They come in packs of five from Halfords for £4 on-line and £5 in the shops.



They are made from copper and have a 0.6mm hole down the middle. The thread is M5.

I drilled out the one on the right to 3mm, almost to the end, to reduce the pressure needed to extrude. They drill easily if the drill is lubricated with a little paraffin. It's a shame they don't work as is, but all the same it is much quicker and easier than turning, drilling and tapping the standard design.

They also simplify my evolving extruder design because the heater block no longer needs a spout. I can simply drill and tap the bottom of the melt chamber M5 and screw these in. I can also change the M8 penny washer for an M6 one. That allows me to reduce the outside diameter of the PEEK collar to 8mm so it can be made from the same stock as the thermal transition. The area of the collar will be less so it will conduct less heat.

The 0.6mm orifice can be made smaller if necessary by filling it with high temperature solder and then drilling it with a fine drill. Solder is very easy to drill so less chance of breaking a fine bit. Also Vik Olliver suggested you can make a small hole by soldering in some fine Nichrome wire and then pulling it out again to leave the hole (solder does not stick to Nichrome).

I haven't tried one yet but I can't see any reason why they won't work well.

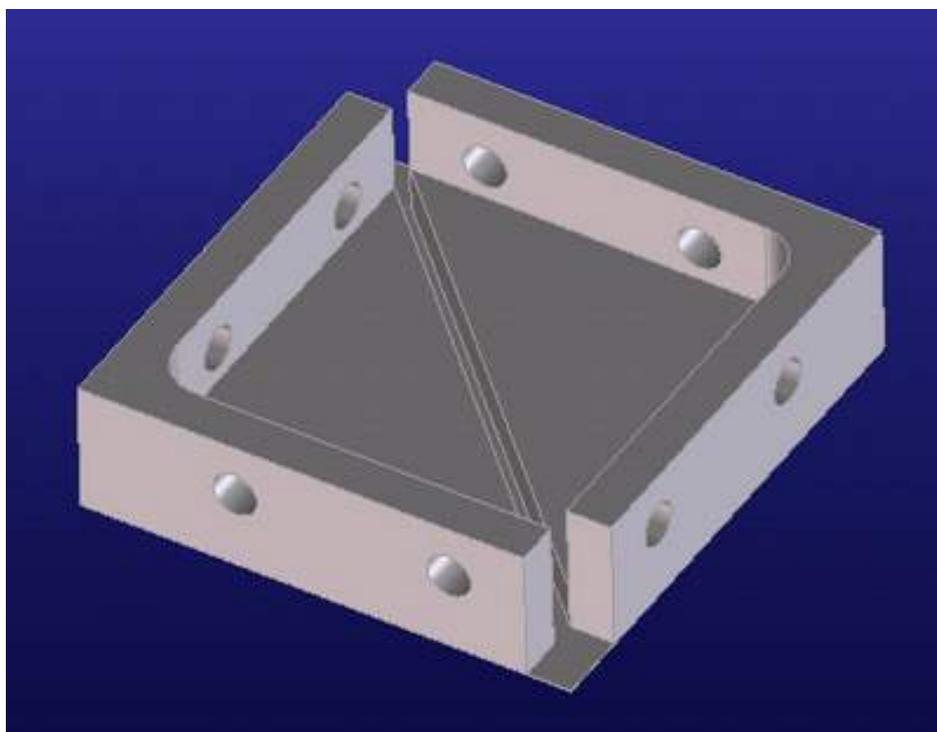
# Siamese twins

Saturday, 7th February 2009 by Nophead

I designed a right angle bracket that I intend to use in pairs. Due to its triangular shape, and the fact that my software creates rectangular rafts, it would be quite wasteful to print them individually.

I am not sure if STL files are supposed to contain more than one object. CoCreate seems to think so but ArtOfIllusion not. However, if you have a set of parts that go together to make one item then it would more convenient to store them in one file and print them together.

A simple workaround is to join all your parts together with an impossibly thin rectangle at base level.



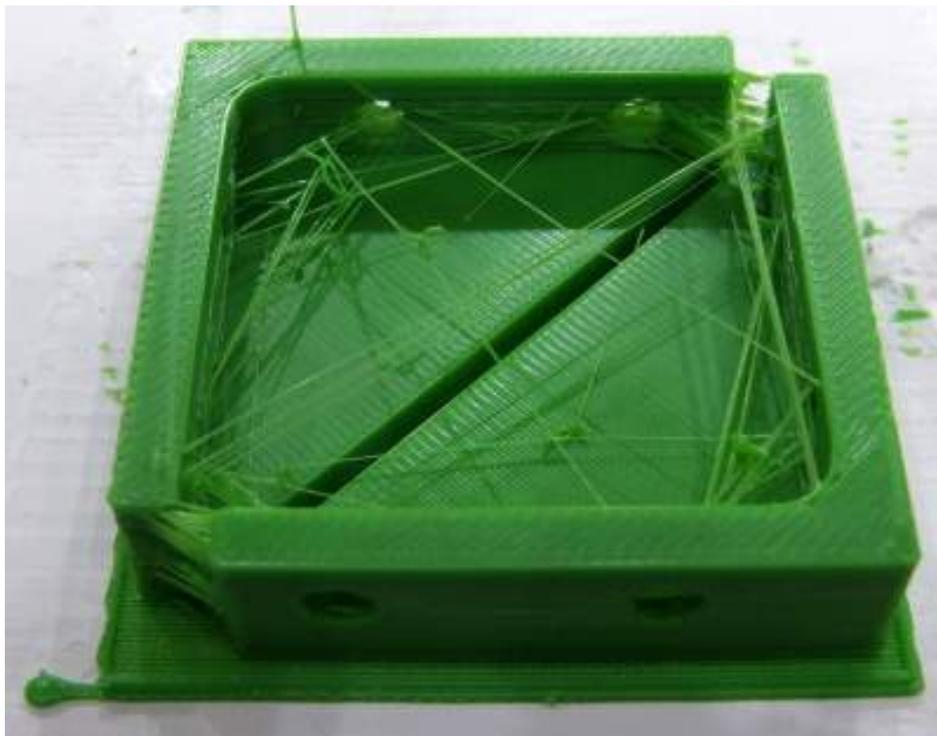
The slice software samples at the middle height of each layer so this 0.1mm base gets missed out completely.

The down side is a bit more stringing as the head moves between the two objects.



These were made with 0.5mm filament through a 0.3mm nozzle and highlighted a problem. As you can see the top surface of the lower triangular part is rippled. The reason is that the filament is not being stretched much, if at all. That means that the sparse infill sags because it is not pulled taught. Three solid layers over the top is not enough to recover to flat as they are not being pulled tight either.

So it appears that some stretch is definitely needed unless you are making a solid object. Here is the same thing made with 0.4mm filament and all is well again.



The upper limit on filament diameter that is usable from a given size of nozzle is somewhat less than the die swell as you need to stretch it a bit.

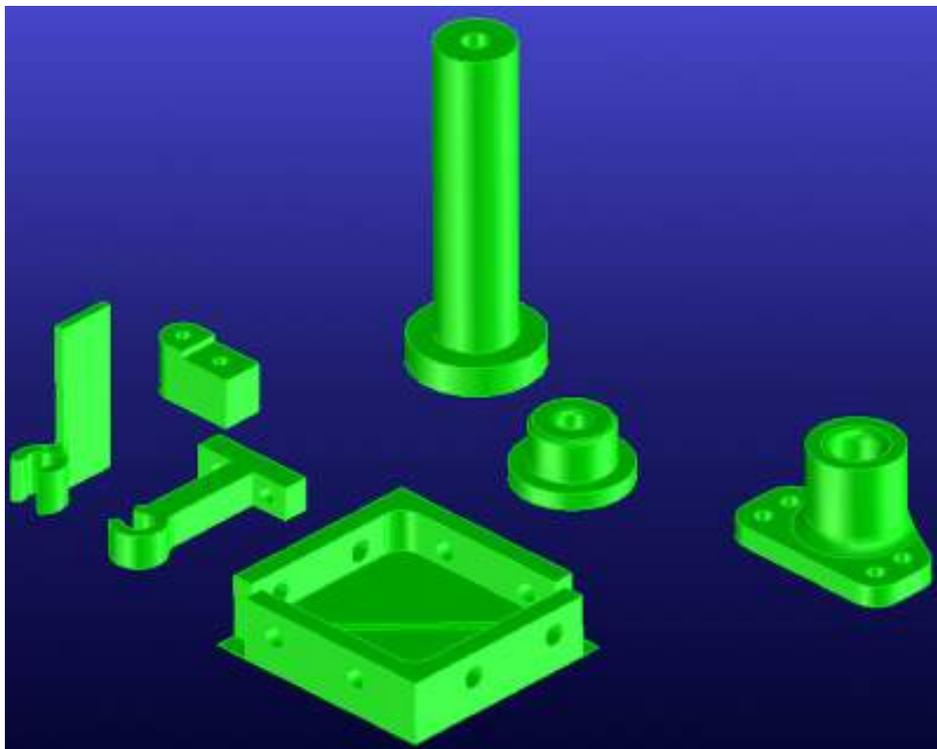
# Lead kebabs

Thursday, 19th February 2009 by Nophead

I am aware that I have often stated things like "HDPE needs more force than ABS to extrude" and a "short thermal transition is easier to push plastic through than a long one" but I have never produced any figures to back up these statements. In fact I don't think anybody on the RepRap project has published any extruder pressure figures. Odd because it is the key piece of information needed to design an extruder and it isn't too hard to measure.

I have put together a test rig to measure the rate of extrusion for a given pressure, which I can vary. That will allow me to evaluate different extruder barrel and nozzle designs quantitatively.

I designed most of the parts in CoCreate and printed them with HydraRaptor.

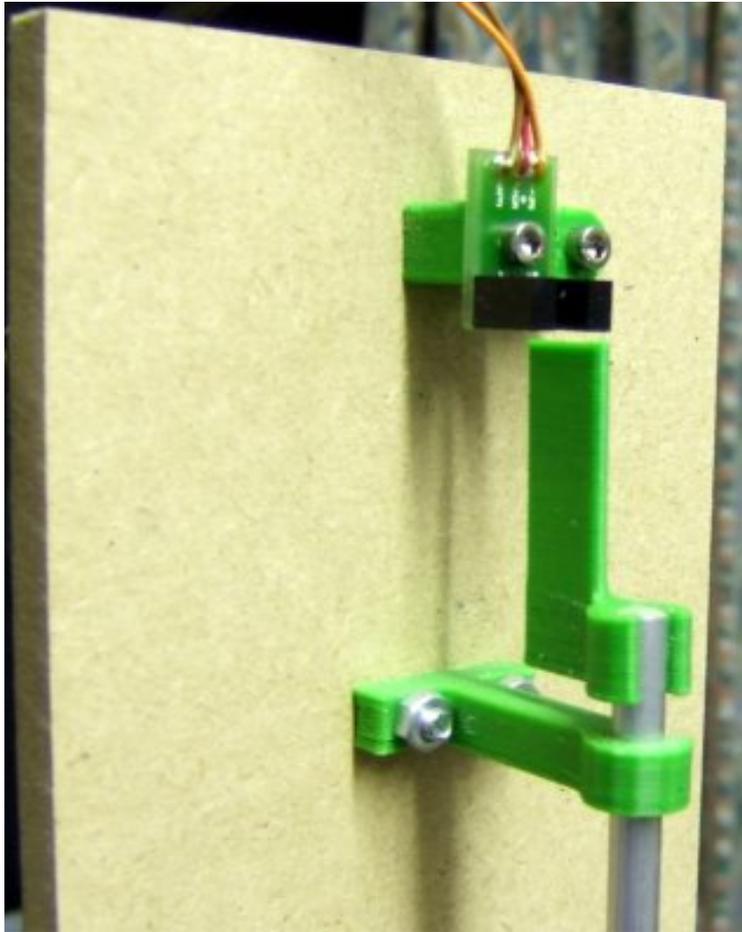


The boss on the far right has mounting holes which match the extruder pump and holds a PTFE cylinder over the filament entrance of the thermal break. I chose PTFE for its low friction. I place a 55mm sample of filament into the cylinder and then push it down with a piston laden with weights. The piston is just the end of a 6mm aluminium rod turned down to 3mm.



An M6 nut stops the green cylindrical saddle, which carries the weights, from sliding down the rod.

The top of the rod is held in line by a guide that it clips into and slides through. A flag 40mm long slides through an opto switch to allow me to measure how long it takes to extrude 40mm of the sample.



The 2mm thick green ABS allows a little IR through, not surprising as it lets some visible light through as well. It was not enough to give a bad logic level but I painted it with black paint to be on the safe side. I should have used black ABS!

The opto connects to the unused filament empty input of HydraRaptor's extruder controller and the heater and thermistor connect to their usual places. A simple Python script tells me how long it takes the flag to pass.

My first idea for weights was to use reels of solder and that is what I designed the rig to accommodate. I managed to muster this little lot, which weigh about 2.2 Kg.



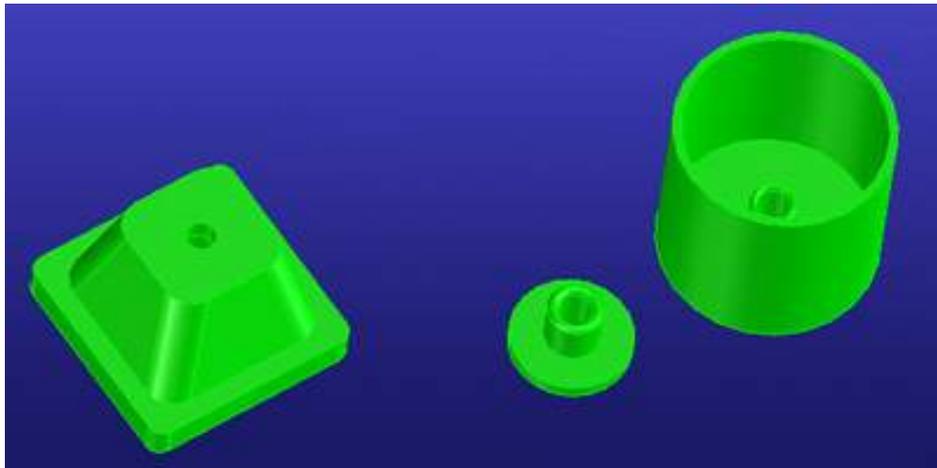
That weight only managed to extrude HDPE at a rate about  $1.1 \text{ mm}^3$ , which is only about 1/3 of the rate I normally extrude at, so I figured I needed about 6Kg to get realistic results.

I needed long thin weights with a hole in the middle, so I ordered some stackable lead sash window weights. I got 10lb, 5lb, 3lb and two 1lb. That allows me to add any weight between 1 and 20lbs in 1lbs increments. A shame they are not in kilograms but sash windows are rather traditional. They cost £50 including shipping so not a cheap solution but they should be handy for measuring motor torque, etc.

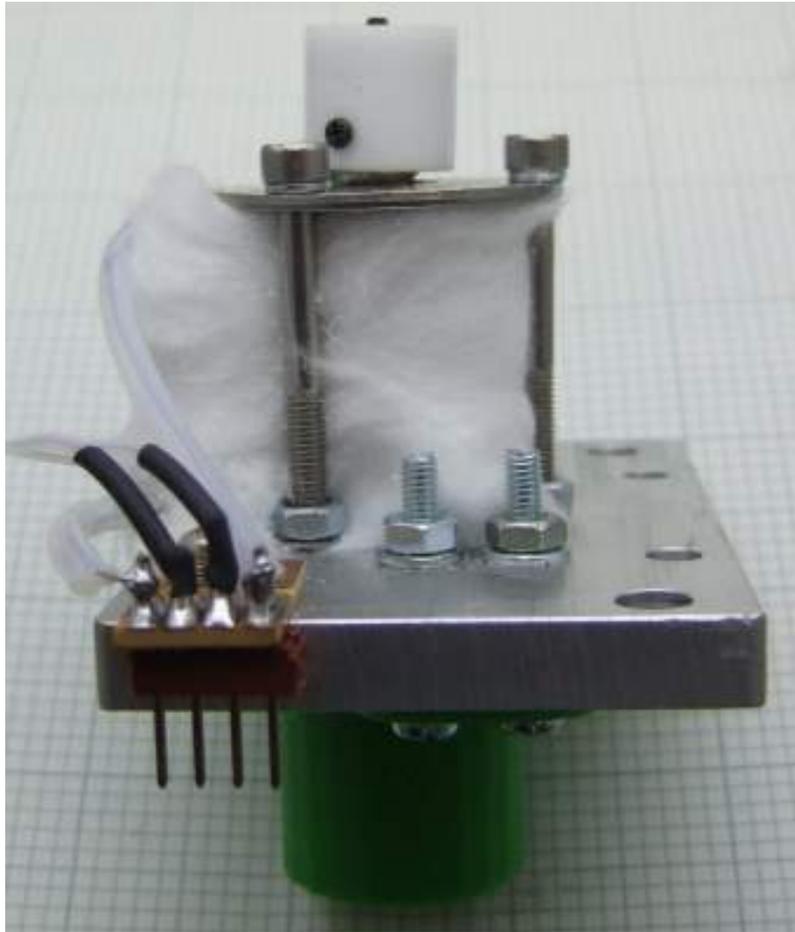


They were supposed to be next day delivery but I ordered on Sunday and got them Thursday. The two one pound weights were not the painted stackable ones I ordered and paid for. When I complained I was told they don't stock them any more. Why they let me order them and invoiced me for them I don't know. I shall not be using that company again!

I made a new saddle for the weights to ride on, a centralising collar for the top and two containers for the unpainted weights.



I also insulated the heater with ceramic wool. That reduced the heatsink temperature from 67°C to 57°C by stopping convected heat from the heater warming it. Unfortunately the boss that holds the PTFE cylinder covers a large area of the heatsink. When I make a new pump I will try to leave more of the aluminium exposed.



With this heater, which is a 20 x 20 x 12 mm block with the thermistor mounted halfway between the heater and the melt chamber, the simple bang-bang temperature control works extremely well. The temperature measured at the thermistor varies by less than 1°C. I have an LED which shows when the heater is on. With previous heater arrangements I see it go on and off at about 0.5 Hz. It does not switch cleanly on and off but fades in and out because of noise in the thermistor reading, i.e. I get PWM for free. With this heater the LED simply gets brighter and dimmer, so I have proportional control with just a single if statement! Who needs PID?

Here is the experimental set-up: -



So far the results are a bit disappointingly inconsistent. Six runs loading it with 55mm of 3.1mm HDPE filament and measuring the time to extrude 40mm of it at 240°C through a 0.5mm nozzle with a weight of 8.27Kg gives the following times: -

90, 95, 100, 114, 163 and 98 seconds.

I have no idea why there is such a big variation. 96s would correspond to  $3.14 \text{ mm}^3/\text{s}$ , which is the normal rate I extrude at. So we are looking at a force of 81N. With a 5mm shaft that Adrian's pinch wheel design uses that would require a 0.2 Nm motor, I think. You need some margin so it would be the top end of what a Nema 17 can provide.

I don't think I counter bored my 0.5mm nozzle like I did my 0.3mm one, so I may be able to reduce the force somewhat. A lot more experimenting required I think.

# If at first you don't succeed ...

Saturday, 21st February 2009 by Nophead

Remember this?



It was my last attempt to get a high temperature extruder idea working. ABS jammed in it, so I put it to one side. This morning I made a slight modification and got it to work extremely well.

The filament was getting stuck in the end of the stainless steel tube where it enters the heater block. I removed the PTFE tape from the threaded joint as I thought that may have been insulating it. That made a small improvement. I could push ABS through it by hand, but only just.

I then flared the hole with this tapered reamer so that it has a 5mm inside diameter at the end, tapering back to 3.6mm, which is the internal diameter of the stainless steel tube.



That made all the difference, I can now extrude my oversized ABS very easily and even HDPE only requires moderate force.

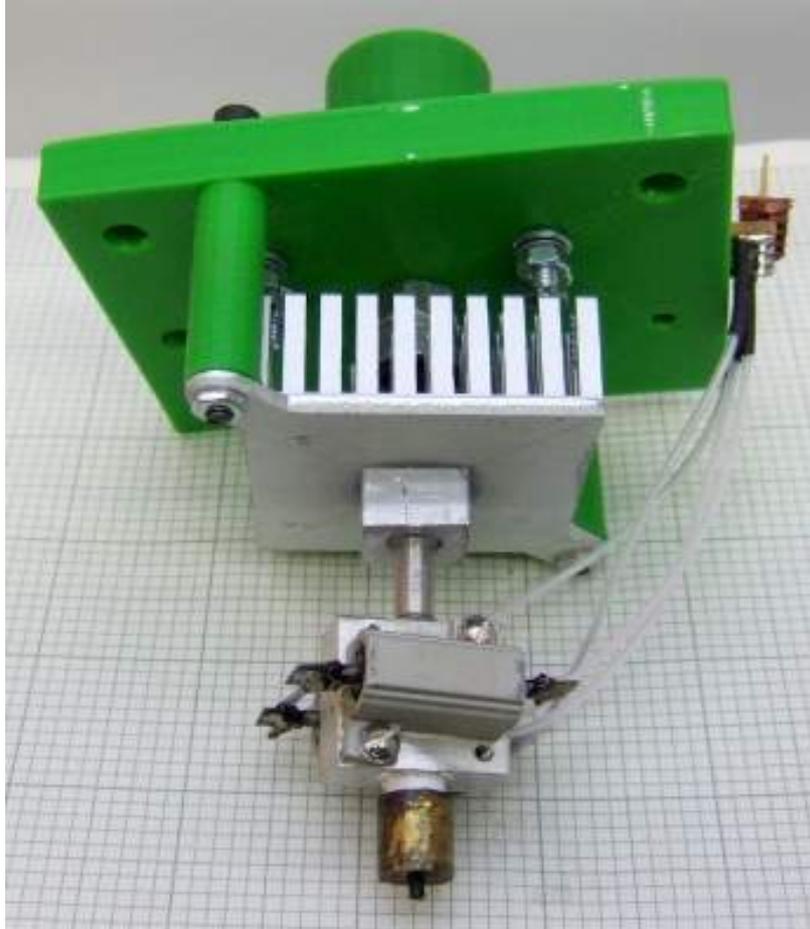
I am not sure why it made so much difference. It makes the wall thinner, so the heat from the heater can get to the plastic easier. It also reduces the friction of the plastic against the inside pipe wall because any downwards motion causes the plastic to come away from the wall.

The next step is to connect it to my test rig to get some comparative pressure figures. My feeling is this extrudes more easily than my PEEK version. That may well benefit from a taper as well.

# Three times better

Monday, 23rd February 2009 by Nophead

I made a plastic mounting plate to allow me to test the new stainless steel extruder in my test rig.



Here it is under test: -

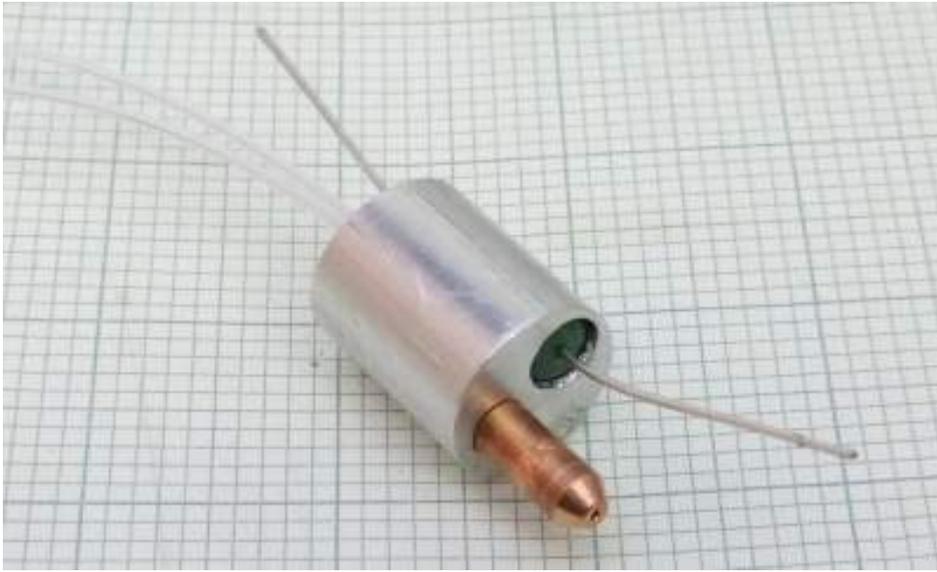


I felt that this design was working well. Now I have the figures to back it up. It is three times better! I.e. with the same weight the extrusion rate is three times faster through the same nozzle and at the same temperature. With 8.27Kg I am now extruding HDPE at  $9.43 \text{ mm}^3/\text{s}$ .

This is a dramatic improvement, especially considering it did not work at all until I added the taper to the end of the transition zone. It shows that the design of the entrance to the extruder is critical and at least as important as the exit.

It is really good news because using stainless steel as the insulator really simplifies the extruder and at the same time extends its temperature range and makes it strong and reliable.

By replacing the heater block with one made with a vitreous enamel resistor and a screw-in welding nozzle, I should have a design that can be made with a drill press, a couple of taps and a die.



I haven't tried the welding tip yet, but now I have a means of comparing it against the standard nozzle.

# Rheology

Friday, 6th March 2009 by Nophead

Rheology is the study of the flow of matter and that is what I have mainly been doing for the past few weeks. When I made my experimental set-up to measure flow rate versus extrusion force I expected to be able to produce some nice graphs for different plastics and different temperatures. I found this excellent page which derives the formula for flow rate  $I$  in a pipe in terms of pressure  $P$ , radius  $a$ , viscosity  $\eta$  and length  $L$ .

$$I = \pi P a^4 / 8\eta L$$

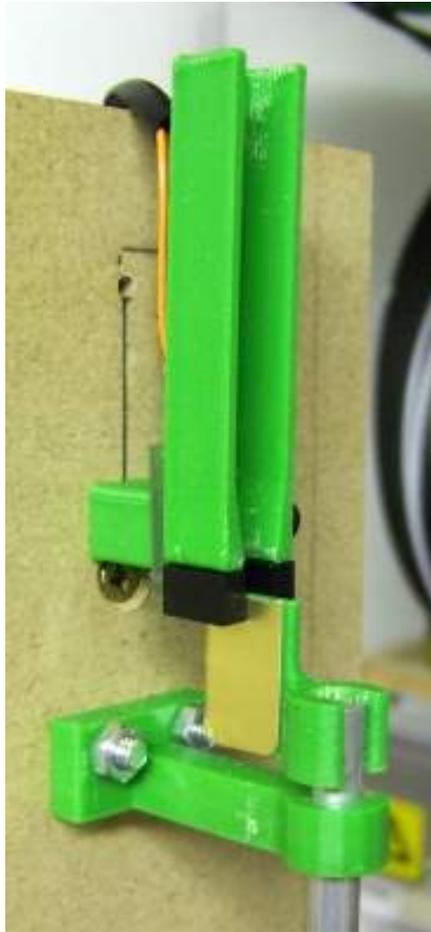
A cylindrical section of flow is considered. Since it flows at a constant speed the force pushing it forwards, which is the pressure plus the viscous drag from the faster inner cylinder, must equal the force retarding it, which is the viscous drag from the slower outer cylinder. Integrating twice yields the formula.

Until recently I had assumed that the large amount of force required to extrude was due to pushing viscous plastic through a tiny hole. The equation shows that for a given flow rate and viscosity, the force is proportional to the length and inversely to the fourth power of the bore.

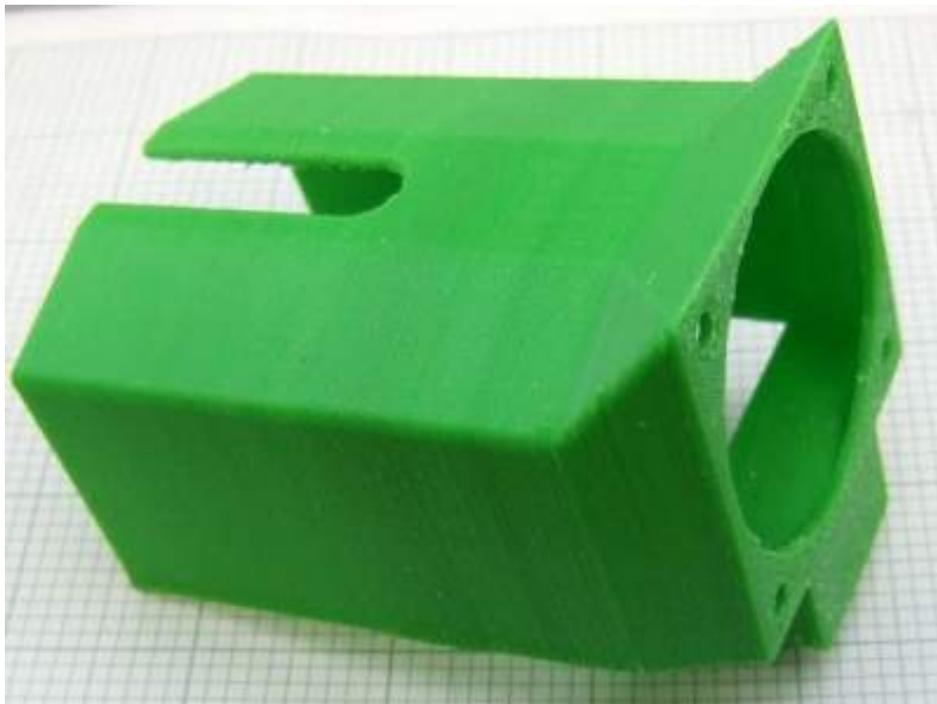
The RepRap V1.1 extruder has a heater barrel that is 45mm long with a 3mm bore and a nozzle with a 0.5mm hole that is about 3mm long, so that would mean that it is about  $(3/0.5)^4 \cdot 3/45 = 86.4$  times harder to push the plastic through the nozzle than the heater. However, that assumes the viscosity is constant. At the point where the plastic melts the viscosity tends towards infinity, so the actual force required to push the filament through the heater is much higher. I have had some extruder configurations where it was hard to push the filament even without the nozzle attached. This simple experiment showed that cutting off 5mm of the heater barrel from the cold end made a significant difference.

Despite these observations I expected the flow rate to be directly proportional to pressure and, with a constant pressure provided by gravity, I expected the flow rate to be constant. In fact the flow rate varies wildly from one run to the next and often increases towards the bottom of the fall. Flow is not directly proportional to pressure, it increases faster than pressure does, and lower pressures seem to give more erratic results.

I tried improving my test equipment to see if I could get more consistency. I reduced the size of the opto tab to record just the last 20mm of the fall, so things had plenty of time to reach equilibrium. I also made a piece to guide the tab into the slot as the weights have a tendency to rotate and make it catch.



I also tried force cooling the heatsink with a small fan. I made a cowling to stop the fan cooling the heater.



This is probably the most complicated shape I have modelled so far. The only mistake I made was

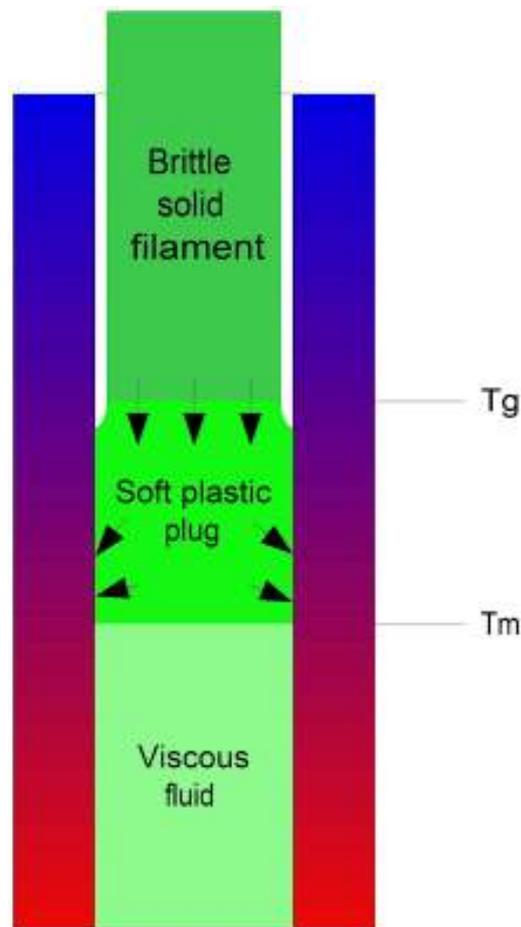
not leaving enough room for two of the nuts to hold the fan. I used self tapping screws instead. If I were designing it again I would put tubular bosses behind the screw holes and use four self tappers. It takes some time to get used to designing in plastic. I tend to use a lot of nuts and bolts, and so do RepRap designs, but they are rarely used in commercial plastic products.



The fan didn't seem to make much difference when extruding ABS, either in the variability or the flow rate. If it did affect the flow rate its effect was lost in the variability.

So after some thought about where the variability was coming from I came to realise that it is an inherently unstable experiment. A lot of the force required is pushing the solid plastic plug through the entrance to the extruder.

For ABS and PLA, which both have glass transitions, the situation in the thermal transition zone looks like this.



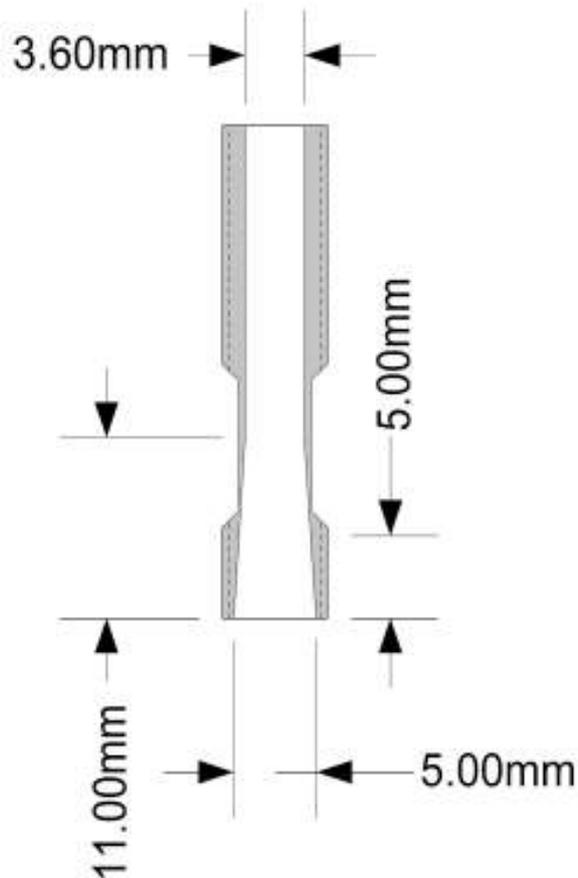
When the filament meets the point in the thermal barrier where the temperature is above  $T_g$  (the glass transition temperature) the filament transitions from its glassy brittle state to a soft rubbery state. In this state it will change shape as force is applied, but it will not flow. Further down it gets to the point where it melts and becomes a very viscous fluid until it warms up to extrusion temperature, where the viscosity is much less. The soft plug gets compressed length-wise by the extrusion pressure, which makes it expand outwards and grip the wall of the insulator. This greatly increases the force required to push the filament, which in turn causes even more outwards force. If the plug is long enough, relative to the coefficient of friction with the wall, it can become impossible to slide it along. Applying more force simply exerts more force against the tube wall, increasing the friction to match the extra push. This is the condition that causes the extruder to jam.

A plug is formed even in plastics without a glass transition, like HDPE and PCL. Molten plastic simply flows backwards until it freezes.

The plug acts like a piston pushing the molten plastic out of the nozzle. Its front face is continually consumed by melting, but the back is replaced by new plastic that is softening.

To prevent the jam, either the coefficient of friction has to be low, or the thermal transition, and hence the plug, has to be short. An outward taper seems to help a lot.

I was asked for a drawing of my tapered stainless steel transition zone, so I drew one from measurements and extrapolation of the taper. The result was scary: -



I hadn't realised I got so close to rupturing the pipe, although it may not actually be as close as the drawing implies. It does work well though.

The reason the plug leads to an unstable result is that the slower the filament travels, the longer the plug is and so the resistance increases and the flow slows further. I.e. a positive feedback effect. It is also why increasing the force gives a disproportionate increase in flow rate. The faster flow reduces the plug length (because the plastic has less time to absorb heat) reducing the resistance, so more pressure gets to the nozzle, increasing the flow rate.

One implication of this effect is that an open loop DC motor is never going to work well. Another is that measuring the force applied to the filament is not a good guide to the nozzle pressure.

I think a more consistent experiment would be to extrude at the desired rate and measure the force applied. The plug would then have a fairly constant length and hence the force should be fairly constant.

Although I cannot get any accurate measurements from the experiment, I did get a rough idea of the force required to extrude various plastics at the extrusion speed I use. I.e. I added weights to get the flow rate around  $\pi \text{ mm}^3$ .

Material	Diameter	Temperature	Nozzle	Weight	Flow rate
HDPE	3.1 mm	240 C	0.5mm	4.60 Kg	3.81 mm <sup>3</sup>
HDPE	3.1 mm	200 C	0.5mm	4.60 Kg	2.39 mm <sup>3</sup>

PCL	2.8 mm	150 C	0.5mm	4.60 Kg	3.44 mm <sup>3</sup>
ABS	2.7 mm	240 C	0.5mm	2.32 Kg	3.67 mm <sup>3</sup>
PLA	2.9 mm	200 C	0.5mm	3.32 Kg	6.95 mm <sup>3</sup>

The viscosity of PCL and PLA drops rapidly with temperature, for example PLA would not extrude at all at 180°C but was very fast at 200°C.

The next thing to try is putting a taper in my PEEK extruder and evaluating the copper welding nozzles.

# Simply better

Saturday, 7th March 2009 by Nophead

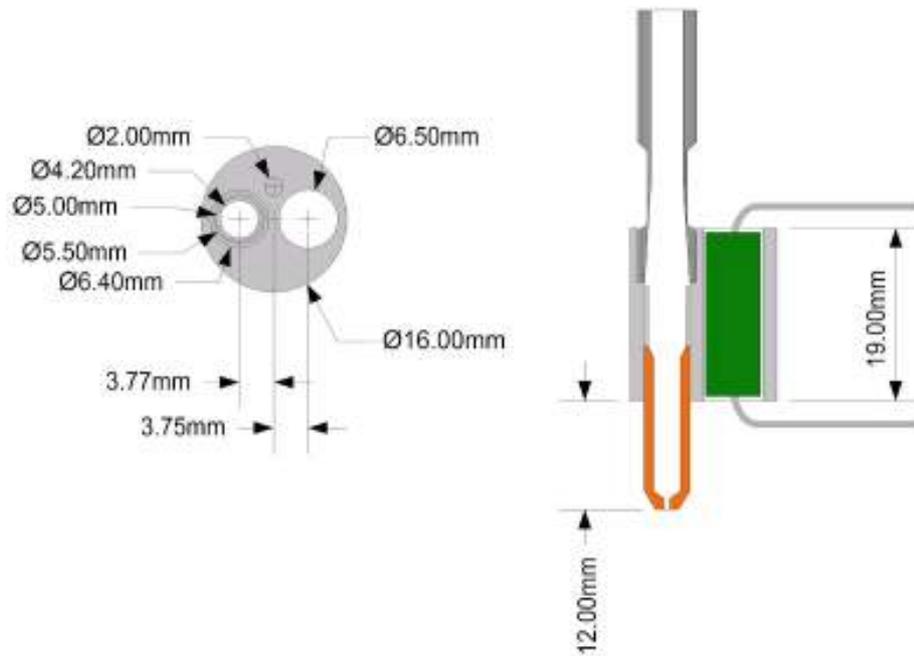
I find it very satisfying when making something simpler also makes it better. I tested the simplified heater / nozzle design using the same stainless steel insulator and heatsink arrangement, so I could get a direct comparison of the results.



The heater warms up a lot faster than the one made with two AL clad resistors. It also extrudes faster and the times are more consistent. ABS pushed with 2.32Kg went from 3.7 mm<sup>3</sup> to 4.6 mm<sup>3</sup>, an increase of 24%. HDPE pushed with 4.6Kg went from 3.8 mm<sup>3</sup> to 9.3 mm<sup>3</sup>!

The nozzle is 0.6mm rather than 0.5mm, which reduces its contribution to the pressure by a factor of 2, but all my other tests have shown that what happens at the other end of the heater dominates the force requirement. As I improve things though, the nozzle hole becomes more significant.

Here are the drawings :-



Although it looks complex it isn't difficult to make with a drill press, drill vice, and some taps and dies.

I glued the thermistor in with Cerastil, but I expect it could just be wrapped in tin foil and jammed in like the ceramic resistor, taking care to insulate the wires of course. I use PTFE sleeving.

I didn't need to seal the threads with PTFE tape. I just screwed them up tight and there was no sign of any leakage.

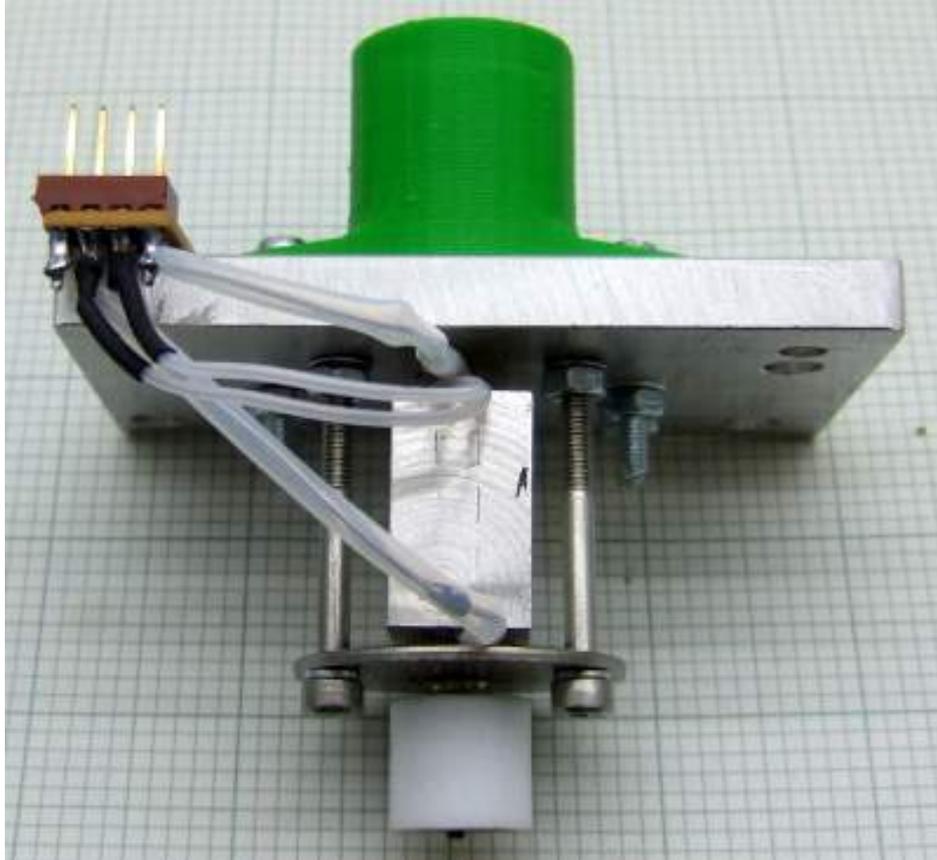
The next thing to try is putting a taper in my PEEK version to see if that can be made to perform as well as this one.

Of course I haven't built anything yet with any of these designs, so caveat emptor.

# Taper relief

Sunday, 8th March 2009 by Nophead

As tapering the stainless steel insulator made so much difference I went back to my PEEK extruder to try the same thing.



I used the tapered reamer to open it up to 5mm at the bottom end.



I had to remove and replace this with the heater hot. You can see where ABS has run up the thread and then burnt when it met the air. This seems to seal the thread as long as the initial leak is slow enough. I don't think HDPE would seal in the same way, so I run ABS first when I assemble an extruder.

The taper made a big difference. HDPE pushed with 4.6Kg went from 1.1 mm<sup>3</sup> to 5.3 mm<sup>3</sup> and the times got more consistent. I think it is beneficial in four ways: -

- It removes the friction of sliding the plug along the wall.
- It increases the bore where the very viscous, just-melted plastic is, reducing the viscous drag by a fourth power.
- It thins the hot end of the insulator making the thermal gradient steeper.
- The wall being thinner and having a bigger surface area will allow more heat flow into the melting plastic.

Foolishly I didn't measure any ABS flow rates before I made this mod. ABS extrudes at 4.5 mm<sup>3</sup> when pushed with 4.6Kg and only 1.3 mm<sup>3</sup> when pushed with 2.3 Kg. This is odd in that the differential between ABS and HDPE is less with this variant.

The performance with HDPE is a bit better than the stainless steel extruder when it was fitted with the same nozzle, but the ABS performance is considerably worse. I can't explain why that would be.

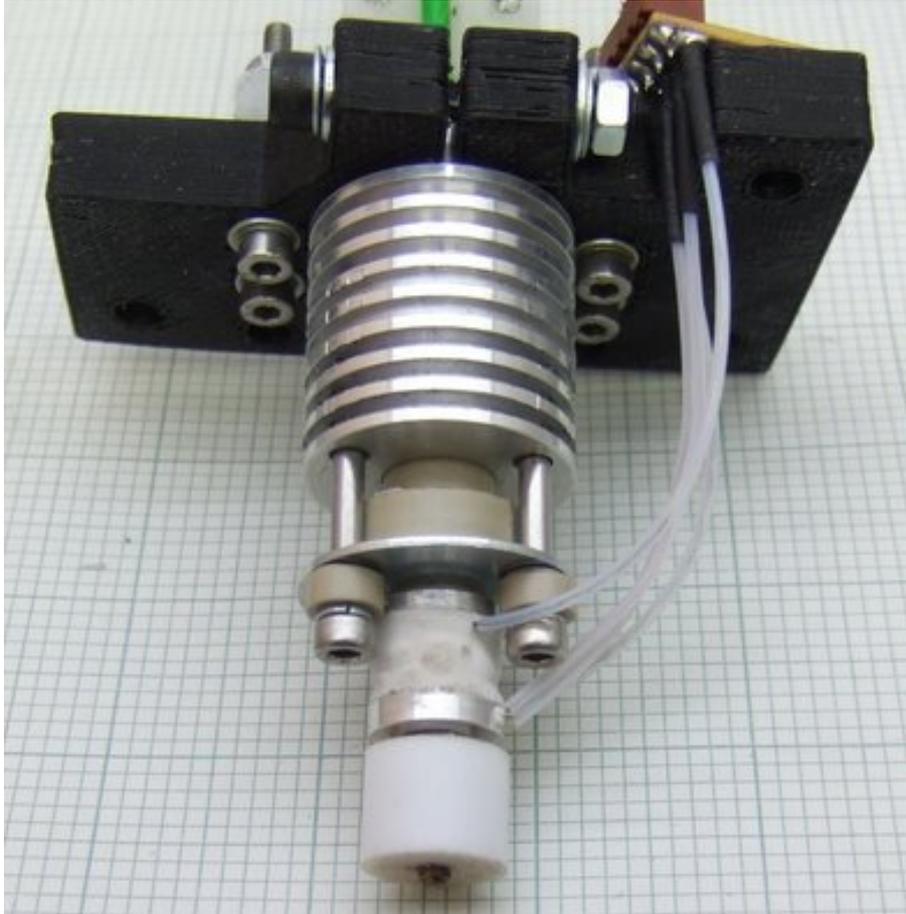
A third variant would be to use a longer PEEK tube with a taper to dispense with the heatsink and hopefully be strong enough without the washer and bolts. I think I will have a look at drive mechanisms for some light relief before coming back to that.

It looks like about 5 Kg force should cover the plastics I have tried so far. I don't think anybody has tried pinch wheel with the slippery plastics (HDPE and PCL) so I will have a go at that.

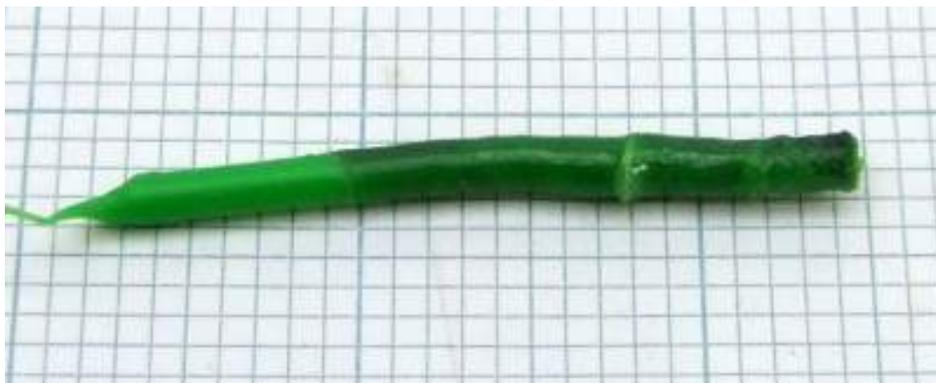
# Constipated Extruder

Sunday, 15th March 2009 by Nophead

My "New Year" extruder, which is the one on HydraRaptor that I use to build things, stopped working while building the first layer of an object. That is the lowest temperature layer, so the plastic is at its most viscous.

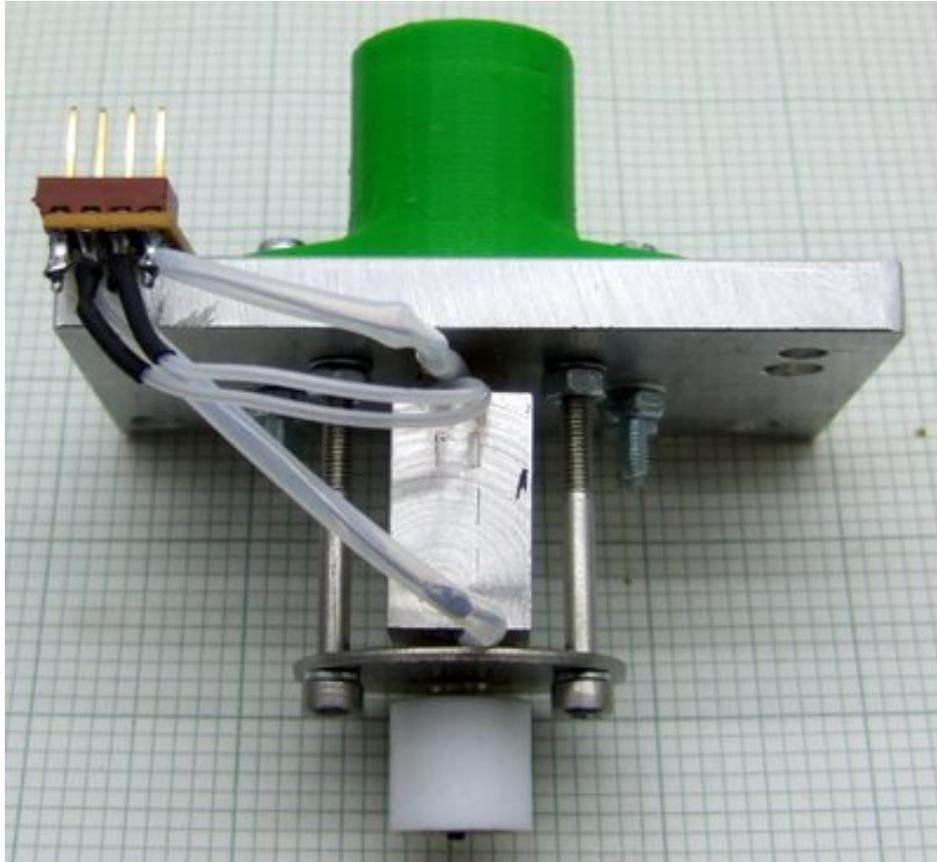


I couldn't get it to work again, so I removed the drive and tried pushing the filament by hand. I couldn't shift it. I measured the temperature of the molten plastic with a thermocouple and it was correct, so I deduced that the nozzle must be blocked. I removed the nozzle and when I pushed the filament this came out: -



It is dark and glassy looking. No idea what caused it, but it seemed to have blocked the nozzle. I cleared it out with a drill and reassembled it. I took the opportunity to measure its performance with my "lead kebab" test jig.

Even though this extruder has a 0.3mm nozzle and no taper in the PEEK insulator, it works better than the tapered PEEK extruder with a 0.5mm nozzle.



The most notable difference is that this one has a much bigger heater chamber, so perhaps a smaller heater bore melts the plastic quicker.

I got this interesting graph of flow against force, averaging over five runs of 20mm : -

## New Year Extruder Performance



I think the steep part of the curve is where the flow through the nozzle dominates the force required and the first part is where the plug friction dominates. The point where I operate it is right on the knee of the curve. I suspect adding a taper would straighten it out, but I don't want to strip down my only working extruder to prove that.

So I don't know what caused the blockage, but it is the second time I have had an extruder block, so it goes to show that a detachable nozzle is advisable.

# Pulling power

Friday, 20th March 2009 by Nophead

There are a lot of extruder drive methods kicking about at the moment, so I decided to evaluate a few by measuring the amount of force they can apply to the plastic before it slips. Rather than build complete extruders, I just made mock ups of the final drive and measured the force they could apply to a spring balance.

My first test was using a splined shaft as a minimalist pinch wheel. This was inspired by Adrian Bowyer's knurled design. I wanted to try it because you can get steppers with splined shafts, so it would be a ready made solution rather than needing a knurling tool and a lathe. I used a 4mm splined shaft that I had lying around. Being that small means the torque required to turn it is quite modest.



I mounted it between ball bearings, which were a press fit into a plastic housing: -



The Meccano gear is just acting as a knob at the moment. I pressed the filament onto it using a skate bearing acting as a roller.



This is my sophisticated test set-up: -



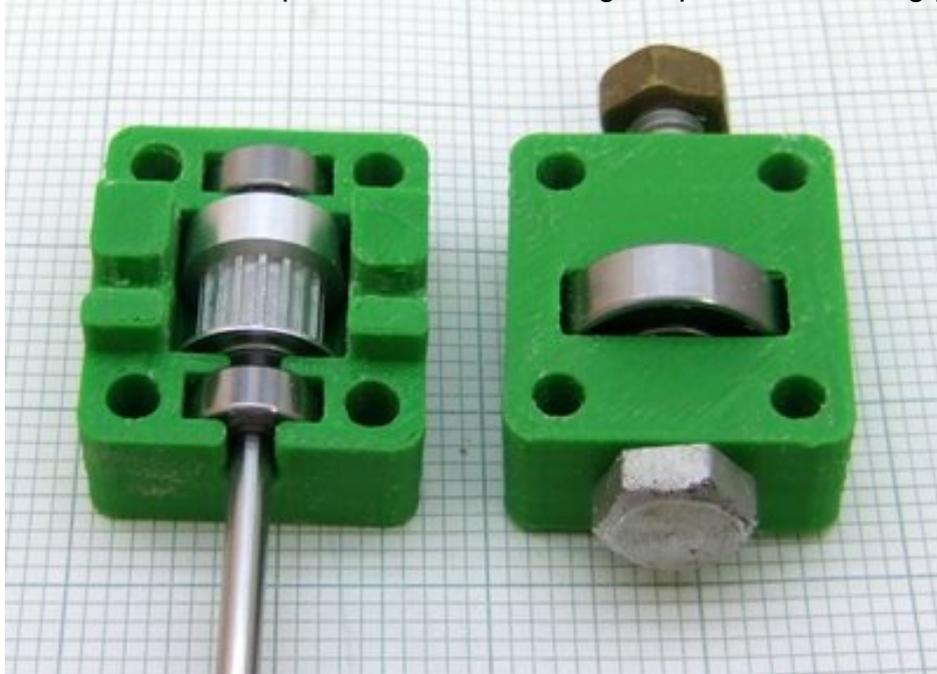
I wind the knob by hand until the filament slips and observe the maximum force for each type of plastic. I noted that tightening the screws past the point where the splines are fully sunk into the filament does not increase grip, it just flattens the plastic more and needs more torque.

The results were: -

PCL	2.5Kg
HDPE	3Kg
ABS	5Kg
PLA	7.5Kg

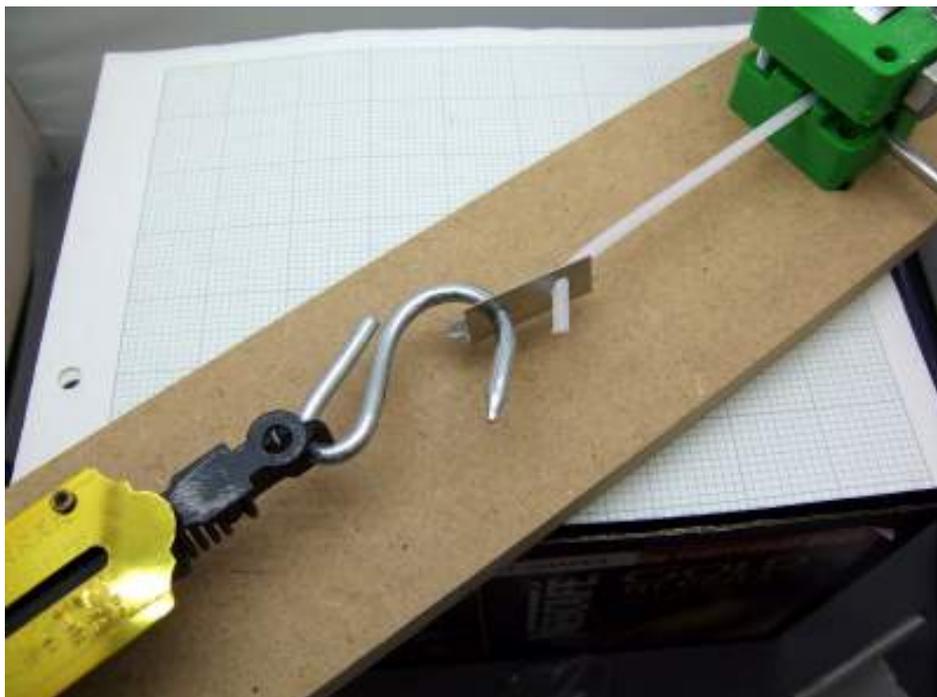
Not surprisingly the grip gets better with the harder plastics. Unfortunately PCL and HDPE need quite a lot of force to extrude, so this drive method is not really good enough for them. A larger diameter shaft should give more grip due to a larger contact area and possibly deeper splines.

The next method I tried was Zach's pinch wheel drive using a square tooth timing pulley.



This needs much higher torque, but gives a much better grip, particularly with the softer plastics. As you might expect the torque is very uneven as the pulley moves from tooth to gap to tooth.

With HDPE, it pulled out of the chuck before slipping, so I switched to an alternative connection to the spring balance.



The results were: -

PCL	4Kg
HDPE	10Kg
ABS	8.5Kg
PLA	>8Kg

PLA slipped from the chuck and snapped when using the alternative coupling, so the true figure is probably higher, but it far exceeds the force needed to extrude PLA anyway.

HDPE has shot up the ranking because although it is quite soft and very slippery, if you can get a grip on it, then it is very tough.

Only PCL is marginal compared to the force needed to extrude it.

Zach uses a bigger opposing wheel, so maybe that would give a bit more contact area.

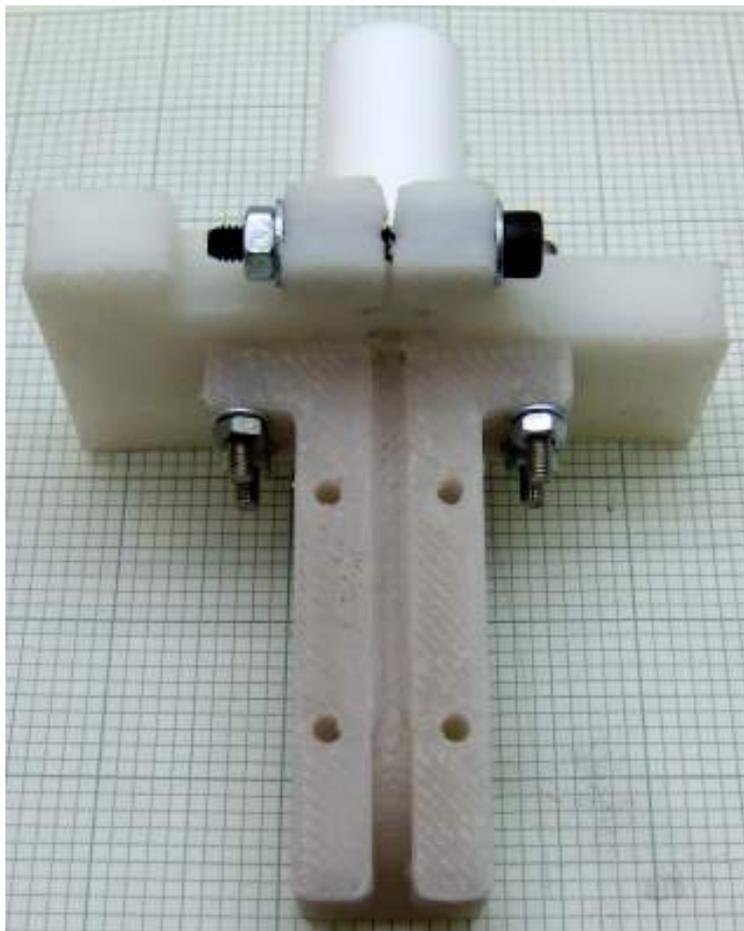
The next thing I tried was the original screw feed design, to get a benchmark, as that is what I have been using so far. It can feed all four plastics reliably, the only problems I have had with it are that the bearings wear out after 100's of hours of use, easy to fix by using ball bearings.

The implementation I used for the test has phosphor bronze bearings and a stainless steel screw. Rather than use threaded rod and try to fasten a nut on the end, I used a hex head bolt. Long ones don't come with enough thread, but you have to run a die over it anyway to sharpen the thread.



It is very hard work tapping stainless steel. For my first attempt I made the mistake of turning the top bearing land before tapping, so that I didn't mar the thread in the lathe chuck. Even though I made the land 3.5mm diameter rather than 3mm, the torque required to tap it actually twisted the shaft where it was turned down. My nice polished bearing surface became a dull and wrinkly spiral!

The other half of the drive is made from HDPE. I think this is a big factor in making it work well as the HDPE is very slippery and doesn't seem to wear much.



A self tapping screw secures the PTFE insulator in the clamp.

The other crucial modification is to angle the screw so it bites gradually at the bottom by spacing the top with two M3 washers and only having two very strong springs at the bottom. Here it is under test: -



The grip was too high for my chuck, and the coupling shown above kept snapping PLA, so I made a brass coupling.



This has a 5mm bore that narrows to a 3mm hole in the bottom. I melt the end of the filament to a blob and feed it through the top.

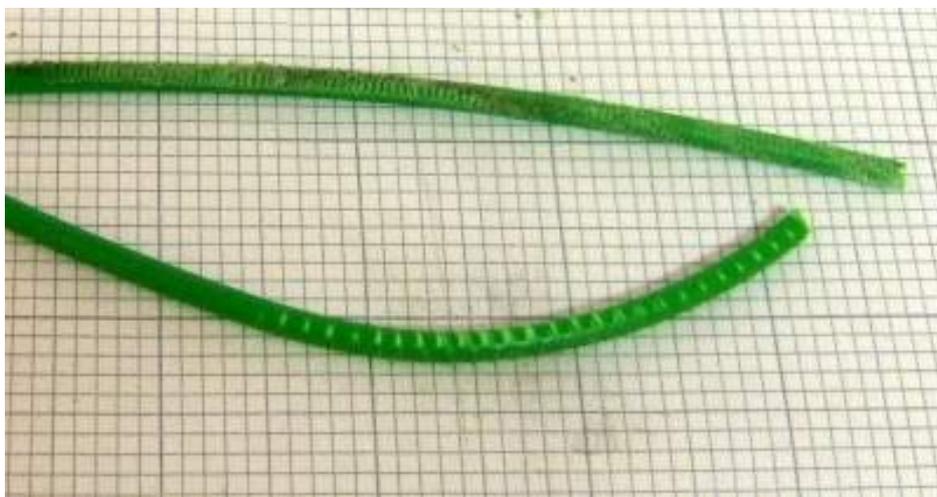
The results were: -

PCL	9Kg
HDPE	>12Kg
ABS	>12Kg
PLA	>12Kg

My spring balance has a maximum reading of 12Kg.

So the screw drive has dramatically more pulling power. It is however, very mechanically inefficient. A lot of torque is wasted by the friction cutting the thread. This can be reduced by shortening the amount of thread engaged. I plan to try it with an opposing roller instead of the HDPE filament guide.

The threaded drive does do more damage to the filament, but the only downside of that seems to be that some dust is produced. The lower filament has been chewed by the timing pulley.

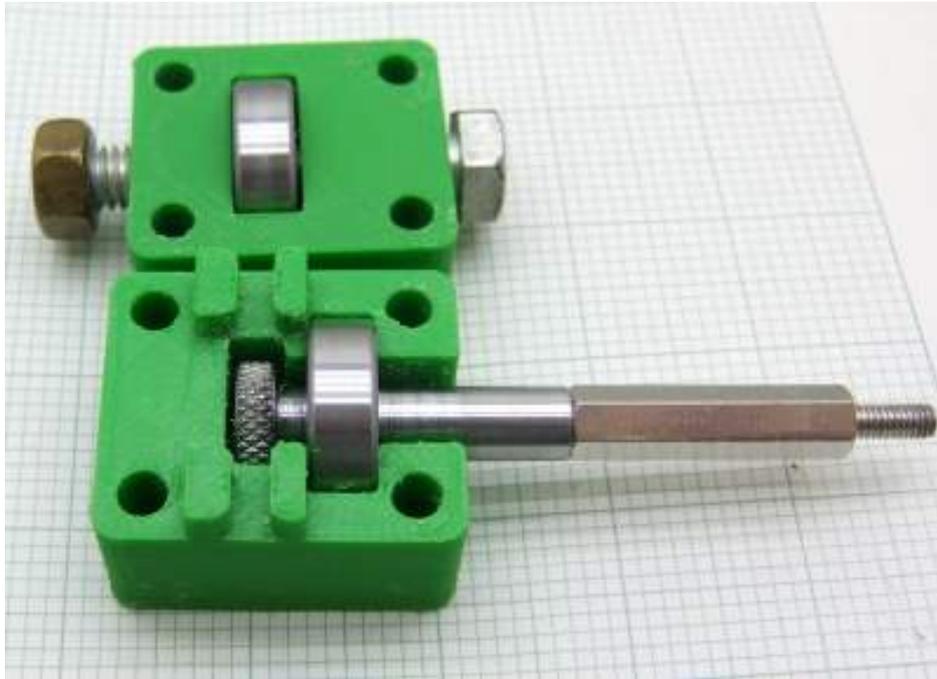


Two other drive methods I plan to try are a knurled shaft and Andy Kirby's worm wheel. That looks like it might have similar grip to a thread, but without as much friction. A lot harder to make though.

# All torque and no traction?

Saturday, 4th April 2009 by Nophead

As promised, I have tested two more drive methods. The first was a 13mm knurled wheel that I had lying around. Handily it was on the end of an 8mm shaft, so I just pushed it through a skate bearing and pressed that into a bearing block.

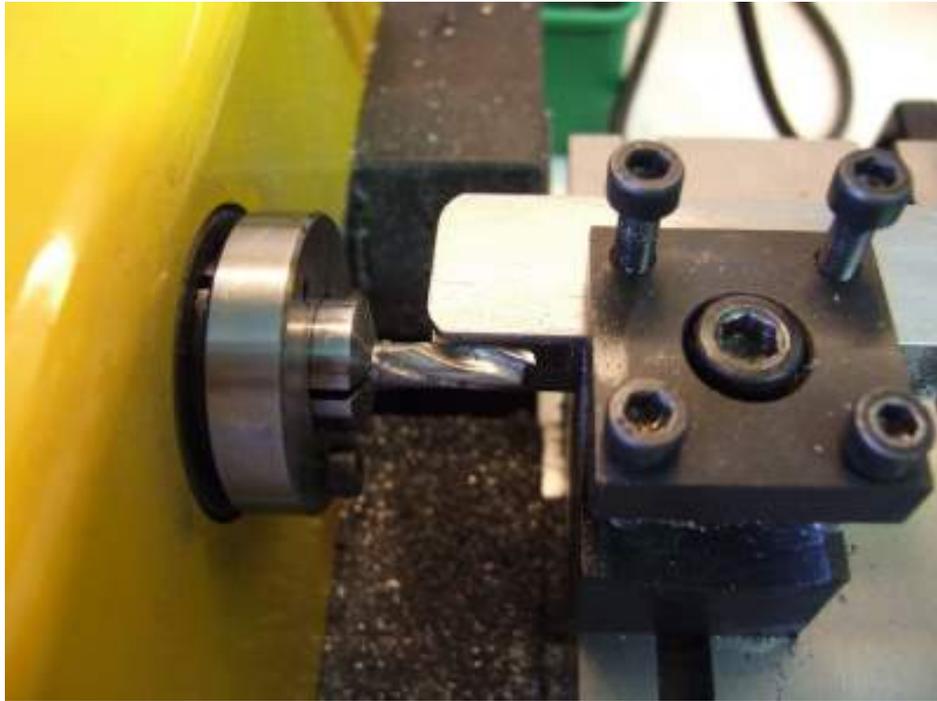


The results were: -

PCL	5Kg
HDPE	10Kg
ABS	12Kg
PLA	>12.5Kg

Surprisingly, a bit better than the same diameter timing pulley that I tested previously. I did have to set the gap quite small for the softer plastics, so the filament comes out quite squashed, which may cause problems downstream. The torque is much more even than with a timing pulley.

The final test was a threaded pulley made by the method aka47 blogged [here](#). Following Andy's instructions, I milled a 6mm slot into a block of steel mounted in my lathe's tool post.



I removed the lathe's chuck and backplate and mounted a collet directly in the spindle taper for best centering and stiffness.

I used the shank of an M4 cap head bolt as an axle and some oiled steel washers for spacers, rather than PTFE as Andy's recommendation.



The next bit is magic. You put a tap bit in the lathe's chuck and advance the pulley towards it by 0.05mm each time the pulley revolves. This is viewed from above: -

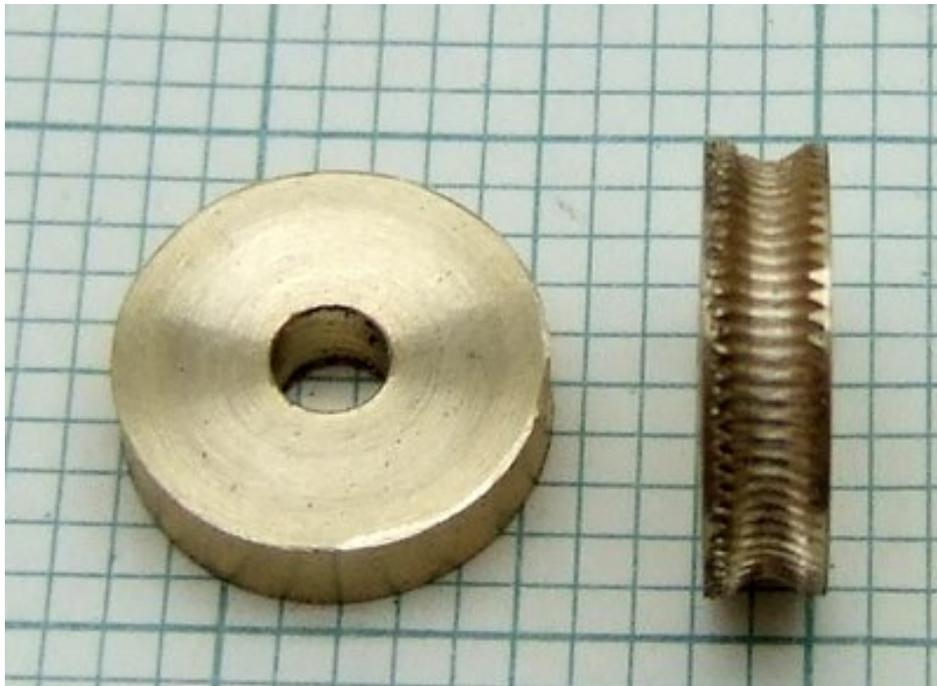


You would imagine that the inner diameter would have to be exactly an integral multiple of the thread pitch, and the same for a knurling tool. Oddly it doesn't seem to matter, and I can't explain why, even having observed it.

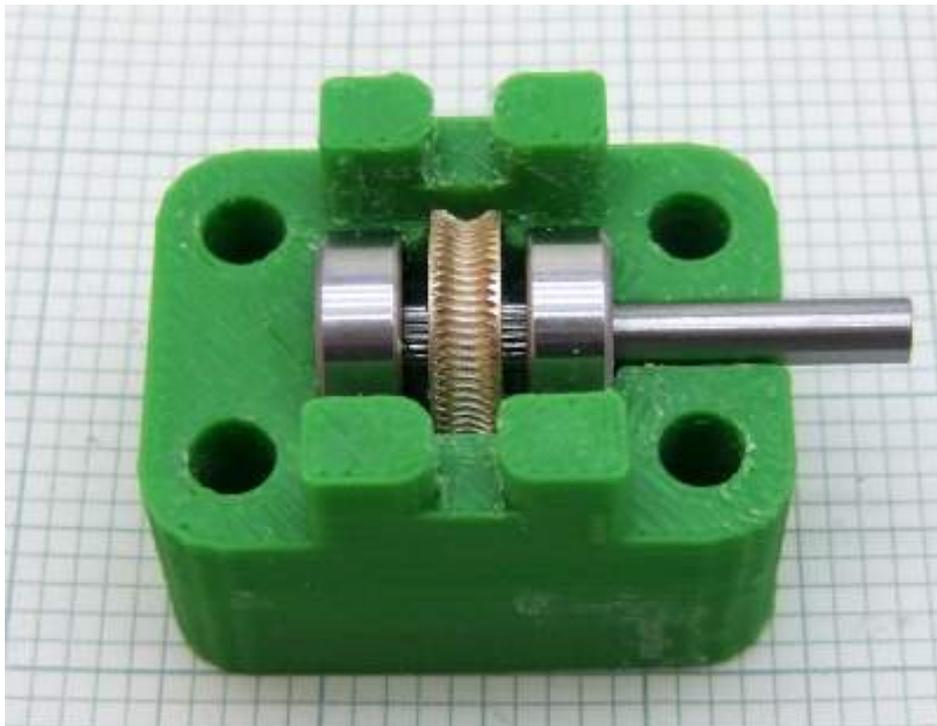
My first attempt was with a M3 x 0.6 tap. I got the height a bit wrong but it was still usable.



The inner diameter of the thread is only 2.4mm, so the filament did not sit in it easily. I made another with an M4 x 0.7 tap, which has an inner diameter of 3.3mm. Perhaps the best fit would be M3.5 x 0.6 but I don't have one of those.



I mounted the pulley on the splined shaft that I had tested before and rewrapped yet another bearing block.



I picked the pulley inner diameter as 13mm to get comparable results with my previous tests.

Ideally it should be smaller to reduce the torque required. For all but the 4mm splined shaft test I had to use a socket wrench to wind the shaft.



This gave the best result of all the pinch wheel tests, but not as good as screw drive on PCL.

PCL	6Kg
HDPE	>12.5Kg
ABS	>12.5Kg
PLA	>12.5Kg

I tried the M3 pulley and that was better still, raising PCL to 8Kg. Here is a summary of all the tests: -

	PCL	HDPE	ABS	PLA
4mm splined shaft	2.5 Kg	3.0 Kg	5.0 Kg	7.5 Kg
13mm timing pulley	4.0 Kg	10.0 Kg	8.5 Kg	>8 Kg
13mm knurled wheel	5.0 Kg	10.0 Kg	12.0 Kg	>12.5 Kg
13mm M4 worm pulley	6.0 Kg	>12.5 Kg	>12.5 Kg	>12.5 Kg
13mm M3 worm pulley	8.0 Kg	>12.5 Kg	>12.5 Kg	>12.5 Kg
M5 thread	9.0 Kg	>12.5 Kg	>12.5 Kg	>12.5 Kg

The red figures are lower or marginal compared to the force required to extrude 0.5mm filament at 16mm/s.

My conclusion is that the worm pulley is the best pinch wheel drive method. It also does the least damage to the filament. It does require a lathe though. On the other hand, using an M5 hex head bolt, a couple of ball bearings and some RP parts requires no lathe and should have better grip.

That is the direction I am going to go.

# Glossy

Tuesday, 7th April 2009 by Nophead

I downloaded [this clever object](#) from Thingiverse. It was created by wizard23 using a parametric CSG evaluator plugin for ArtOfIllusion that he and the other the guys at [MetaLab](#) are developing.



The two halves screw together and fit perfectly.



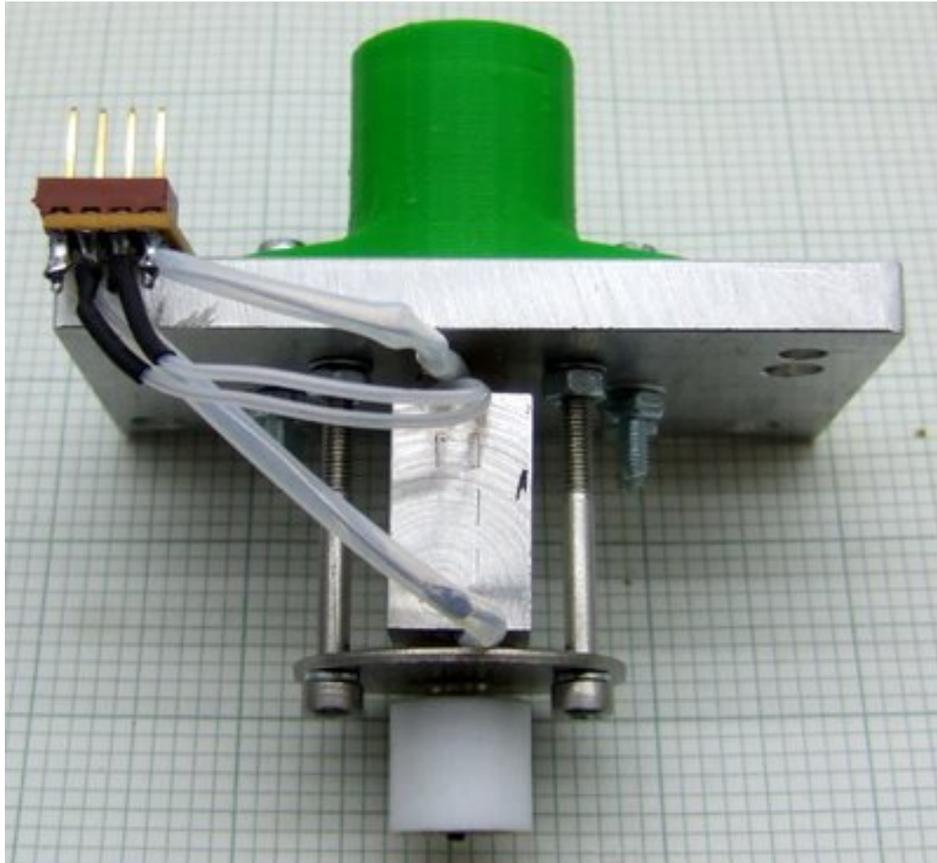
I gave it a glossy finish by painting it with acetone. It looks like it is still wet but it actually dries almost instantly.

# More weight lifting

Thursday, 9th April 2009 by Nophead

I have had a couple of extruder jams recently when doing the first layer infill. I do that at 195°C to avoid it sticking to the raft. It seemed that ABS was much harder to extrude at that temperature, so I did a range of tests to find out how flow rate and force vary with temperature.

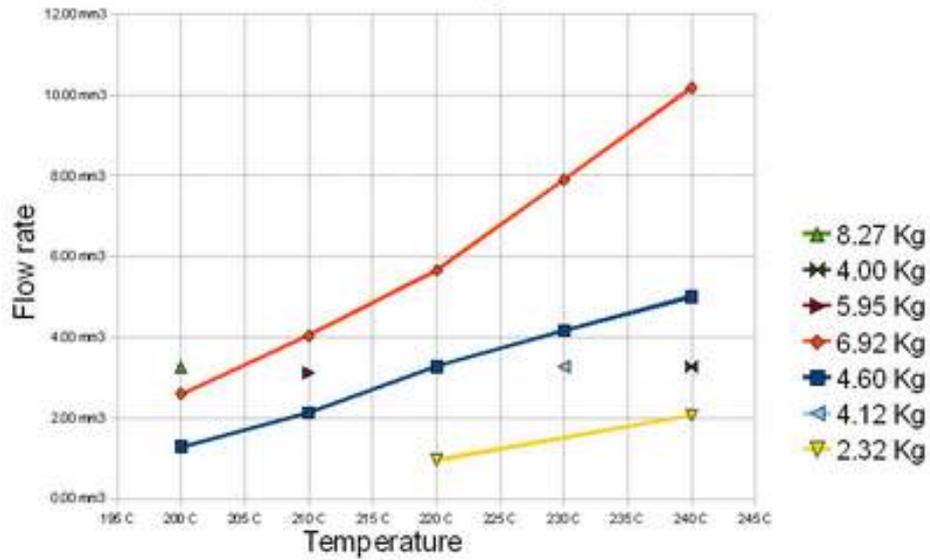
I used my lead kebab test rig with this extruder, which has a 0.5mm nozzle: -



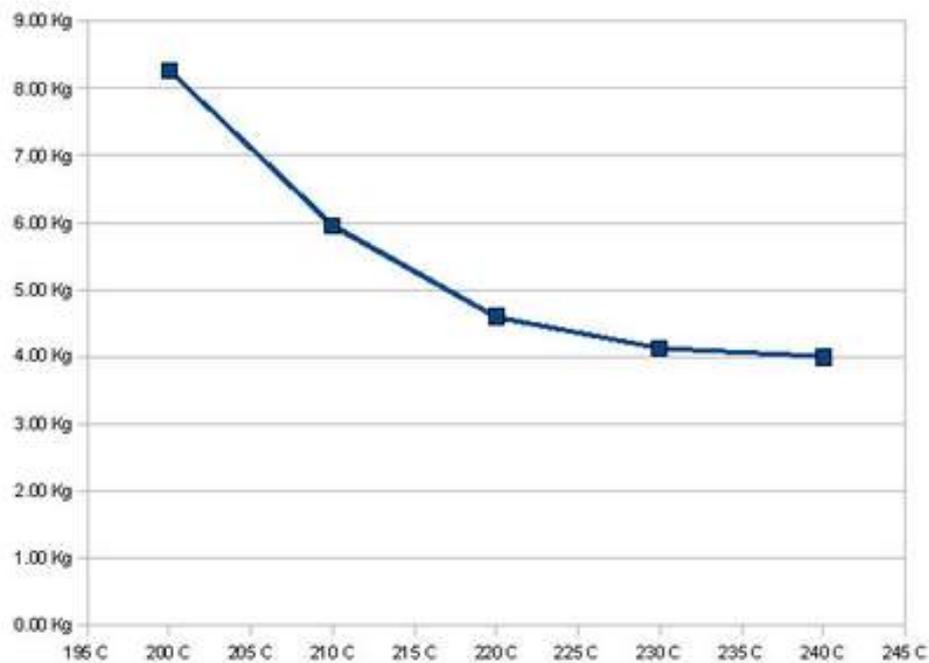
Most measurements are averaged over 8 tests of extruding 40mm of filament, so it took a long time to get these results.

These are the basic measurements: -

## Flow v Temperature



Flow rate for a given force seems to increase fairly linearly with temperature. The single points are the weight that I found gave about my normal extrusion rate of  $\pi \text{ mm}^3/\text{s}$ . Below are the same points plotted against weight: -



So force does increase rapidly below 220°C.

## Nutty tip

Saturday, 11th April 2009 by Nophead

If you want to use a nut, but find there is not enough room for it, here is an easy bodge that I have used a few times: -

Just take a nut one size below, drill it out and tap it to the size you wanted. This is very easy to do because the outer thread size of the smaller nut is about the same as the tap drill size of the bigger one, so you only really have to drill the thread away.



The nut on the left is a proper M5 nut, the one on the right is an M4 nut tapped to M5. Obviously it will have a lower maximum load but it can get you out of a hole.

# Dinosaur?

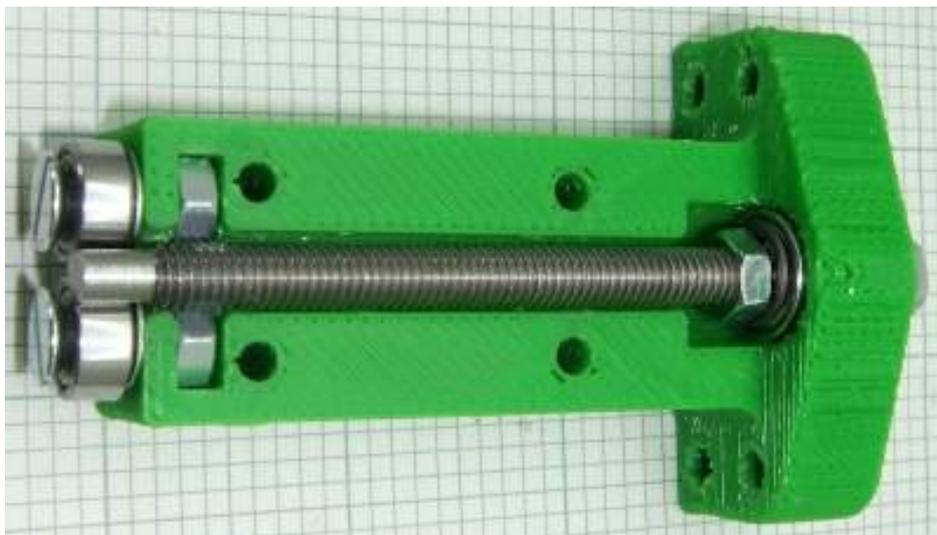
Monday, 13th April 2009 by Nophead

This may be an evolutionary dead end, with the move to stepper motors and pinch wheels, but I wanted to try a couple of things that have been on my "to try" list for a long time.

The main issue that I have had with the pump part of the original extruder is that the bearings wear out fairly quickly. Both the half bearings themselves and the lands on the shaft. One problem is that being only half bearings, any lubrication soon gets carried away by the plastic.

The best lifetime I have had is with stainless steel bearings and a stainless steel shaft. The downside of a stainless steel shaft is that you cannot solder a nut on to provide the drive. I have found two ways round this:-

1. Use a hex head bolt. For some reason stainless steel bolts never seem to have thread all the way to the top. Since the thread needs to be sharpened with a die anyway, it can be extended at the same time. It is hard work tapping stainless steel though. You need a split die, set to its biggest diameter to start with, and you need cutting compound. The hex head allows you to get a good grip to stop it turning and the original thread makes it easy to start off square.
  2. Drill through the nut and shaft and insert a pin. If, like me, you break lots of drills then broken drill shafts make perfect pins. I now buy drill bits in packs of five or ten!
- I replaced the two half bearings with three ball bearings. At the top is an M5 bearing to take the axial thrust. At the bottom I use two M4 bearings as rollers to take the radial load.



The downside of this arrangement is that you still need to turn a land on the bottom of the shaft. It could probably be done with a file and drill though. It actually works without removing the thread, but I expect it might wear away the rollers.

This design works but there are a few things I would change if I built another: -

I made it compatible with the existing filament guide to avoid having to reconfigure my machine for HDPE. Ideally the screw holes at the bottom end need to move out to allow longer bolts to hold the rollers and the size needs increasing from M3 as the threads strip eventually.

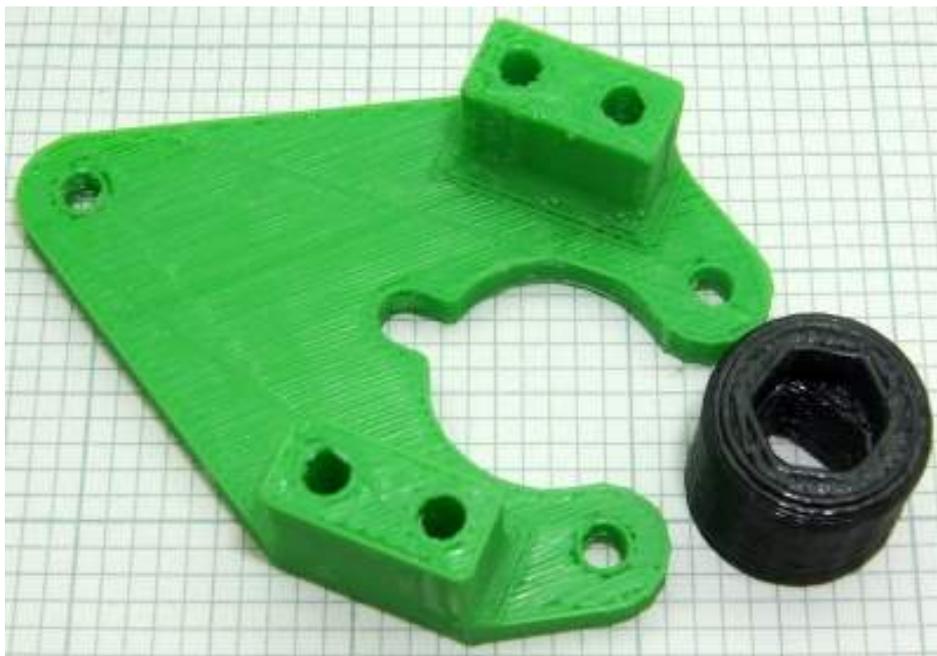
I left clearance to allow the top bearing to be inserted from below, but left no access to the nuts. Consequently it was very difficult to assemble and I had to make undersized nuts.

I used the smallest outside diameter bearings I could find for the given inside diameter. That was a mistake because it is hard not to foul the outer part of the bearing with a washer as the moving part is so small. Star washers seem to just grip the inner and provide enough standoff to clear the outer. I used counter sunk heads to clear the outer face of the rollers. I expect larger diameter bearings use bigger balls, so perhaps have higher ratings.

All easy things to put right with a design iteration.

Another thing I have been meaning to try is the GM17 gearmotor. I have had some for a long time, but without a second shaft, adding a shaft encoder is not trivial, as it is with the GM3. Solarbotics now sell a cheap magnetic encoder that fits inside the casing, making it a more attractive proposition.

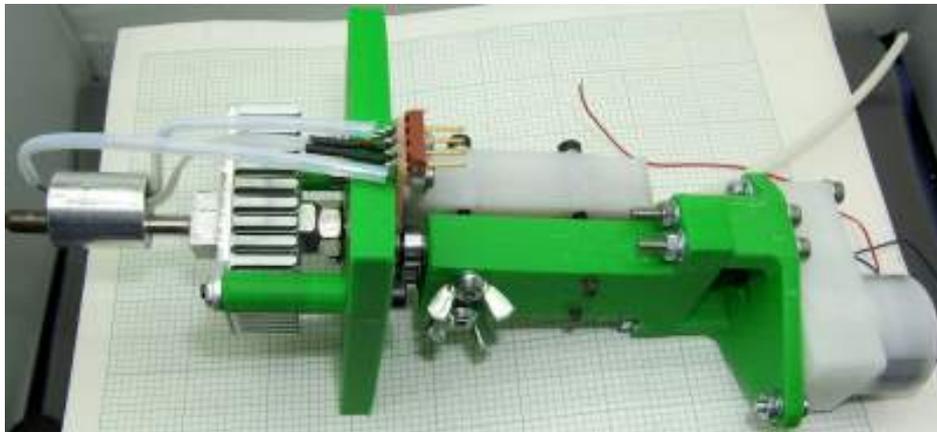
To fit the motor in place of the GM3 a new mounting bracket and a shorter version of the shaft coupler is needed.



Here is the completed pump: -



And here it is built up into an extruder: -



I am waiting for the magnetic encoder to come from Canada so I tested it open loop with a couple of bench power supplies.

The GM17 is a bit quieter than the GM3, but not that much when heavily loaded. It extrudes at a similar rate, but the speed seems to vary a lot with load, so it would be useless without closed loop control. It seems to labour and get quite hot at 12V, so I don't imagine its life would be a lot better than GM3. It overruns a lot when the power is disconnected, so it would need a full H-bridge and reverse thrust to get decent stopping.

I still have lots of things to try: stepper drive, a roller instead of the filament guide, an offset screw drive to avoid the rollers.

# Unexpected find

Monday, 13th April 2009 by Nophead

While looking through my collection of salvaged stepper motors I found a couple of NEMA17s. This one came out of the hard drive in the first PC that I bought, an 80286 AT clone for about £1200 in the 1980's.



All the subsequent hard drives I have owned had voice coil head servos, but this one, which was a full height,  $5\frac{1}{4}$ " , 20MB MFM drive, was built more like a floppy drive with a stepper motor to move the heads.

The motor had a plastic wheel with an endstop on it preventing it making more than one revolution. On removing it I was surprised to find that it was also a resonance damping device.



It seems to consist of a brass flywheel isolated from the shaft by a ball bearing, but coupled to it with a viscous fluid, probably some type of oil. I think it behaves like an electrical snubber, which is a resistor and a capacitor in series use to dampen voltage transients. I think this will have an analogous effect on velocity transients.

I found a similar motor in a  $5\frac{1}{4}$  floppy drive, but that was uni-polar whereas this one is bi-polar, and it did not have the damper. It looks like they were pushing the performance of steppers as far as they could before moving to voice coil servos.

I don't know if it still works, it is more than 20 years old and I damaged it a bit removing it from the shaft as it was glued on. I don't think I will need it when driving a high friction, low inertial load like an extruder drive.

# Threading

Tuesday, 14th April 2009 by Nophead

Khiralay asked me to explain how I manage to put a thread on stainless steel, so here goes.

Aluminium and brass are fairly easy to thread, but stainless steel is very tough. In order to make it easier you need to use a split die and a holder designed for one.

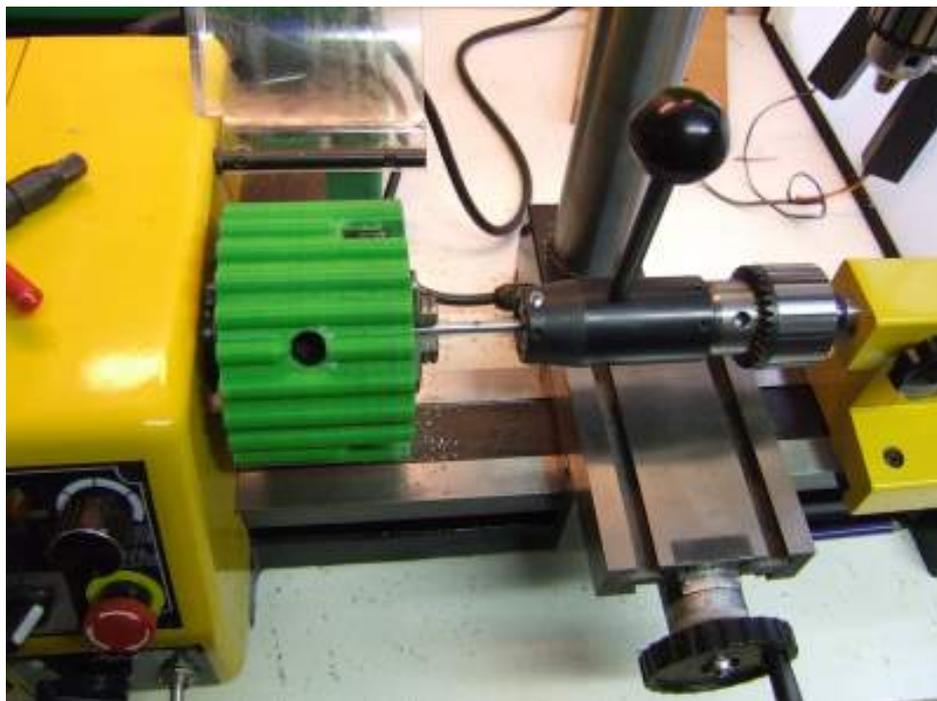


By tightening the middle pointed screw you can force the die to spread and increase the diameter of the thread a little. That allows you to make a first pass that doesn't cut as deep, so does not require as much force. By loosening the middle screw and tightening the outer ones you can reduce the thread diameter and make a second pass.

Another thing that makes it easier is to use cutting compound to lubricate it. I use Trefolex on Adrian Bowyer's recommendation. It is a sort of green lardy gunk.



To start off you need to align the rod or tube that you are threading orthogonally to the plane of the die. The easiest way to do this is with a lathe. You put the work piece in the headstock chuck and mount the die in a die holder that slides along a bar held in the tailstock.



You then turn the chuck with one hand and the die holder with the other. I use the handy chuck grip that I RepRapped, but a chuck key can be used to turn the chuck in 1/3 turn increments.

You need to go about half a turn forward and then one third of a turn backwards to break the chips off. If you don't it may jam.

When you start you need to feed the die against the workpiece with some force, but once the thread is started it feeds itself.

It is unlikely the chuck will have enough grip for cutting a stainless steel thread from scratch. You may have to file some flats on the stock.

If you don't have a lathe, the next best thing is to put the workpiece in the chuck of a drill press and put the hand die holder flat on the bed. Let the weight of the head press the work into the die and turn the chuck by hand. Once started you can put the work in a vice and spin the die holder.

Using a die to extend the thread on a hex head bolt is much easier because you start on the existing thread and you can hold the head in a chuck or a vice.

# GM17 stepper hack

Wednesday, 22nd April 2009 by Nophead

I have thought for some time that the best thing to drive an extruder with would be a small stepper with a gearbox. The reason being is that a stepper motor has close to zero efficiency when moving slowly. Power is speed multiplied by torque, so as speed increases the efficiency increases until the torque falls away due to inductance. A gearbox allows a much smaller stepper to be used because it can be run faster producing more power.

I had a look for steppers with gearboxes, but they seem to be ridiculously expensive. An alternative idea was to replace the DC motor in a gear motor with a small stepper. I couldn't find one with the correct ratio though until Solarbotics started selling replacement gears for the GM17. They allow the standard ratio of 1:228 to be changed to 1:104 or 1:51.



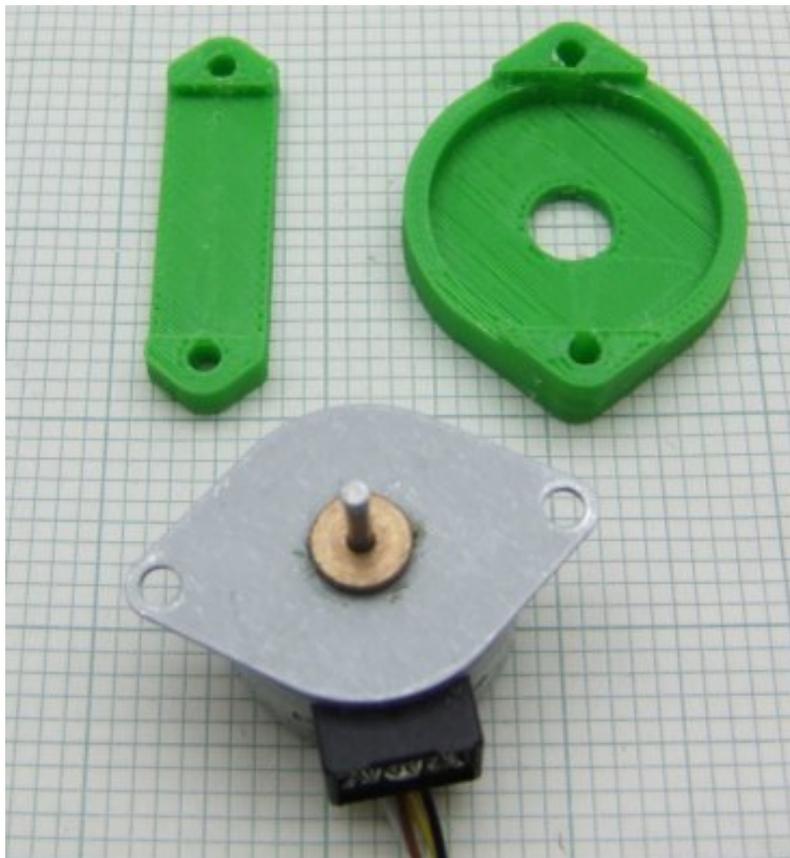
That makes the GM17 very flexible as they also do a magnetic shaft encoder with an integral H-bridge driver. Great for robotics, but it seems a bit under powered for an extruder.



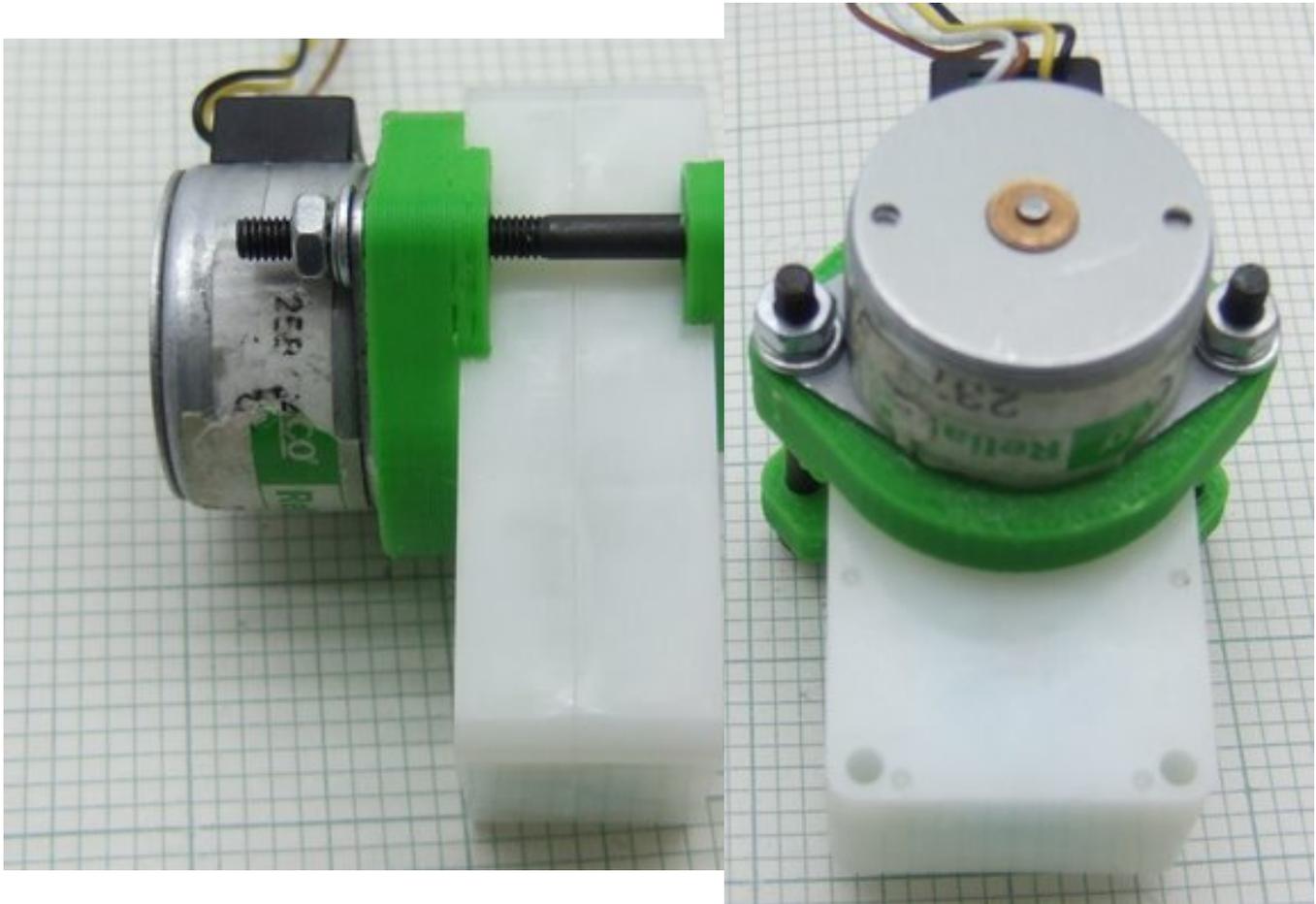
The motor is about the same size, and has the same shaft, as the tiny steppers I got from Jameco

for my first attempt at an alternative Z-axis.

I cut away the plastic cylinder that holds the motor and RepRapped an adapter flange to mount the stepper.



Here it is assembled: -



The small pinion gear is a push fit on the motor shaft, but I found that with the higher torque from the stepper I had to glue it on.

I can run the stepper up to 1000 steps / second in full step mode, with a 12V constant voltage bipolar drive. The step angle is 15° so that is 2500 RPM! It has very little torque at that speed, but it gets multiplied by the gear ratio of course.

At lower speeds the current increases and the motor gets way too hot at 12V, so it needs to be driven from a constant current drive. That is what I was intending to use anyway.

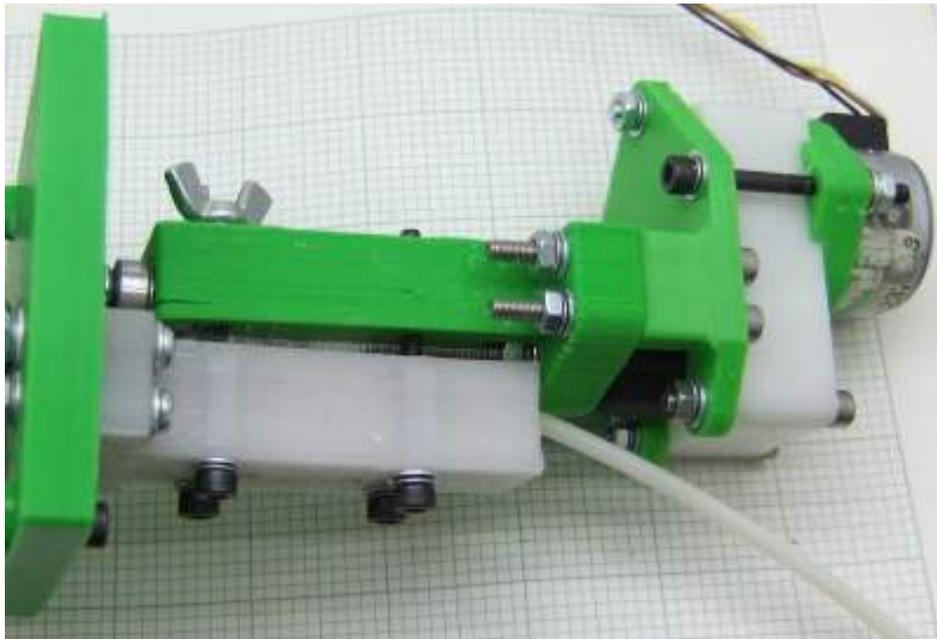
Jameco state the holding torque as 140 g.cm, so I have calculated the torque after the gearbox, assuming no losses as: -

Ratio	Max Speed	Max Torque
51	49 RPM	0.7 Nm
104	24 RPM	1.4 Nm
228	11 RPM	3.1 Nm

It seems remarkably high as NEMA23 steppers are only about 1 Nm. Note that the max speed is for about zero torque and the max torque is for about zero speed.

I attached it to a screw drive extruder and managed to extrude ABS at a rate equivalent to 0.5mm

@ 19 mm/s with a step rate of 800 pps using the 1:51 gears.



So similar performance to a GM3 with these advantages: -

- No brushes to wear out.
- No shaft encoder and PID software.
- No RFI suppressor.
- Only needs step and direction pins on the controlling micro rather than two or three H-bridge controls and two quadrature inputs.
- The output shaft and final gear are one piece, whereas on the GM3 the plastic shaft is on a metal splined shaft that can slip.
- The clutch is one gear back from the output, so gives higher torque before slipping.

The interesting thing is that the projected torque figures indicate that it would be able to do a pinch wheel extruder with its original gear set. I will give that a go next.

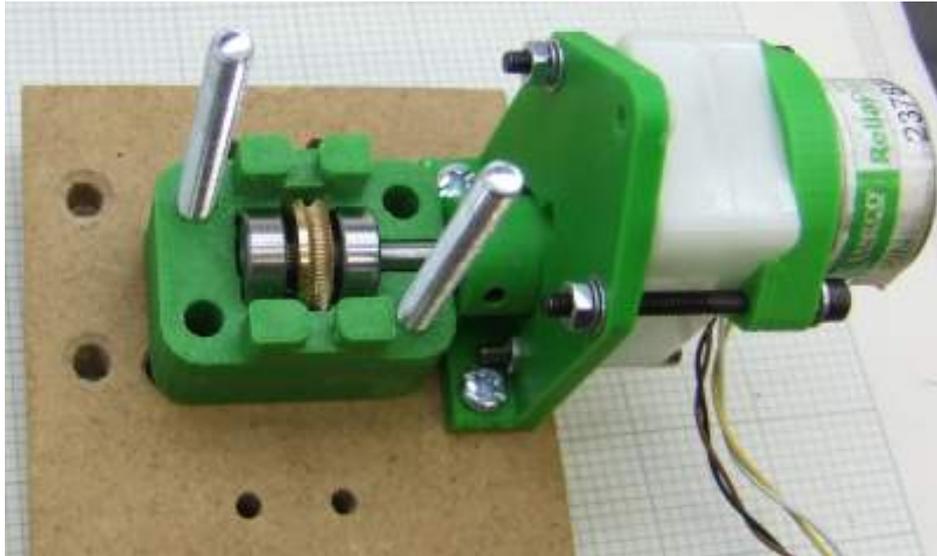
I think the cost is about the same as a NEMA17. The advantage is it is smaller and lighter, the disadvantage is it would need separate bearings and a coupler. The NEMA17 will go a lot faster, but has less torque.

# Tiny stepper torques big

Sunday, 26th April 2009 by Nophead

Having calculated that the tiny stepper and GM17 gearbox combination should be able to drive a pinch wheel, I made a lash up to test the theory.

When you have a 3D printer "lash up" is probably not the right term as quite sophisticated parts can be made easily.



Here it is pulling a spring balance with a piece of HDPE filament.



It got to 10 Kg and then the coupling from the GM17 to the 4mm shaft of the pinch wheel let go.



Not surprising given the torque involved and the fact that it was made with 25% fill. I made it again with 100% fill. I can't remember the last time I made a solid part.



It is coupled to the shaft with a hexagonal steel insert drilled out to 4mm and tapped M3 for a set screw onto a flat on the shaft.



With the 100% fill coupler it easily pulled the scale to the end, i.e 12.5Kg. The motor was powered from 8V (to stop it getting too hot) and stepped at 200pps. With a step angle of 15°, the GM17 default gear ratio of 228:1 and a 13mm pinch wheel that gives a feed rate of: -

$$200 \cdot 15 / 360 \cdot 1 / 228 \cdot 13 \cdot \pi = 1.5 \text{ mm/s.}$$

That would give an output rate of 54mm of 0.5mm filament per second. I think that is comparable to the rates Adrian Bowyer has reported from a NEMA17, but it only weighs about 60g whereas a NEMA17 is about 200g. There are a lot more parts to wear out though, so a NEMA17 may be a better option. Darwin can easily throw 200g about and HydraRaptor is moving table, so the head weight has little relevance.

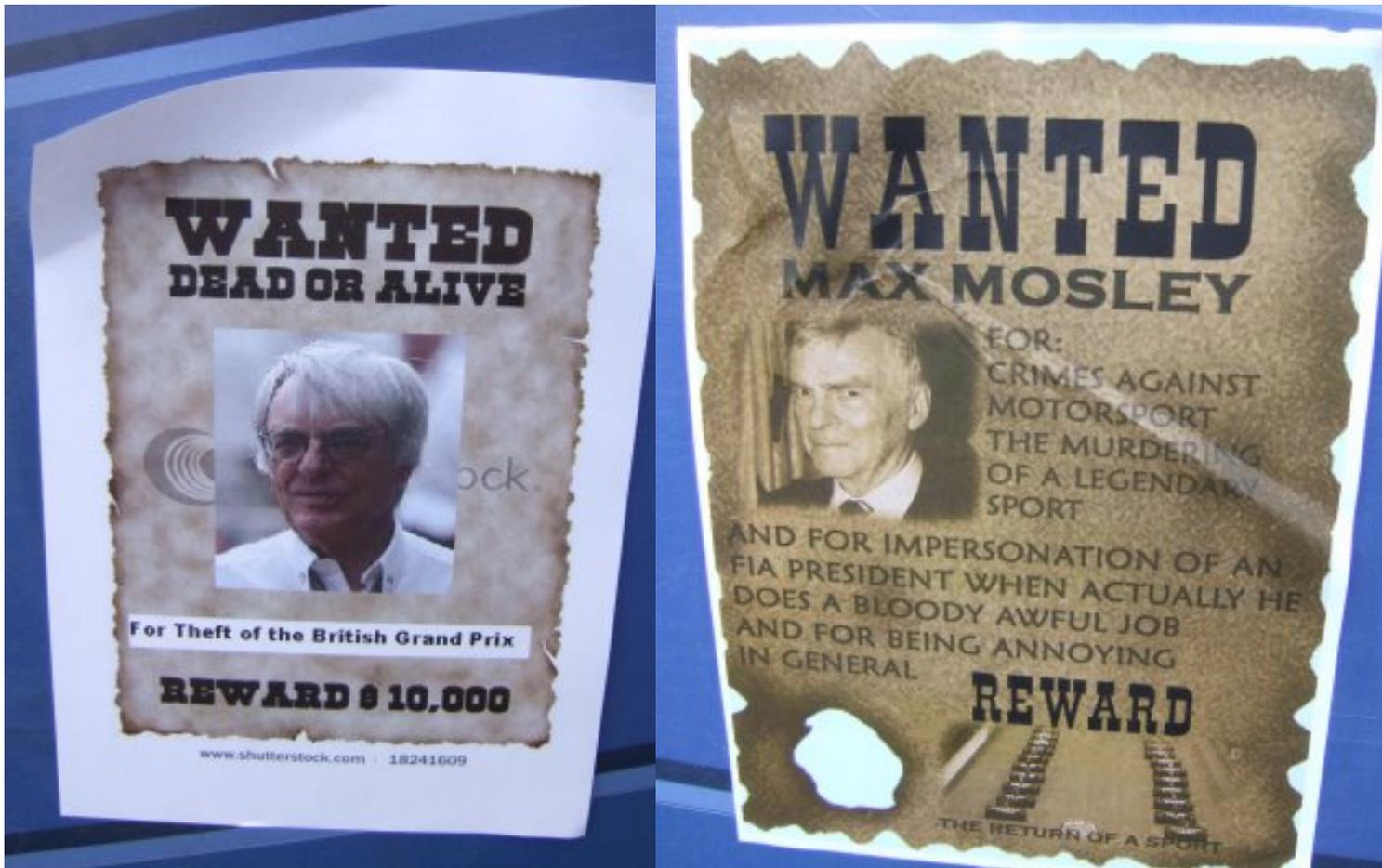
I have some NEMA17's arriving this week. I tried one from an old disc drive but it didn't have much torque. I don't know if that was because it had aged in the 20+ years I have had it or whether modern motors are much better.

# Back to Blog

Friday, 26th June 2009 by Nophead

Sorry I haven't posted here for a couple of months. A few people emailed me to see if I was OK, still alive, etc. No sinister reason for not blogging, I have just been on holiday, had a few weekends away, beer festivals, BBQ's, etc, and also visited the British F1 Grand Prix.





I have also been designing a new extruder controller for HydraRaptor with a stepper motor drive. I normally build electronics straight from brain to veroboard, no schematics or planning, I just pick up the parts and solder them in. That is very quick and efficient but does not leave any design record.

I decided I wanted a micro stepping bipolar drive and the only sensible way to do that is with an off the shelf chip. They are nearly all fine pitch surface mount these days so I needed to use a PCB. It is probably 10 years since I last designed a PCB and I have never used Kicad before so it took me quite a while to get it sorted. Now that I have sent the board away for manufacture I can catch up with the blogging.

## \$8 Z-axis

Sunday, 19th July 2009 by Nophead

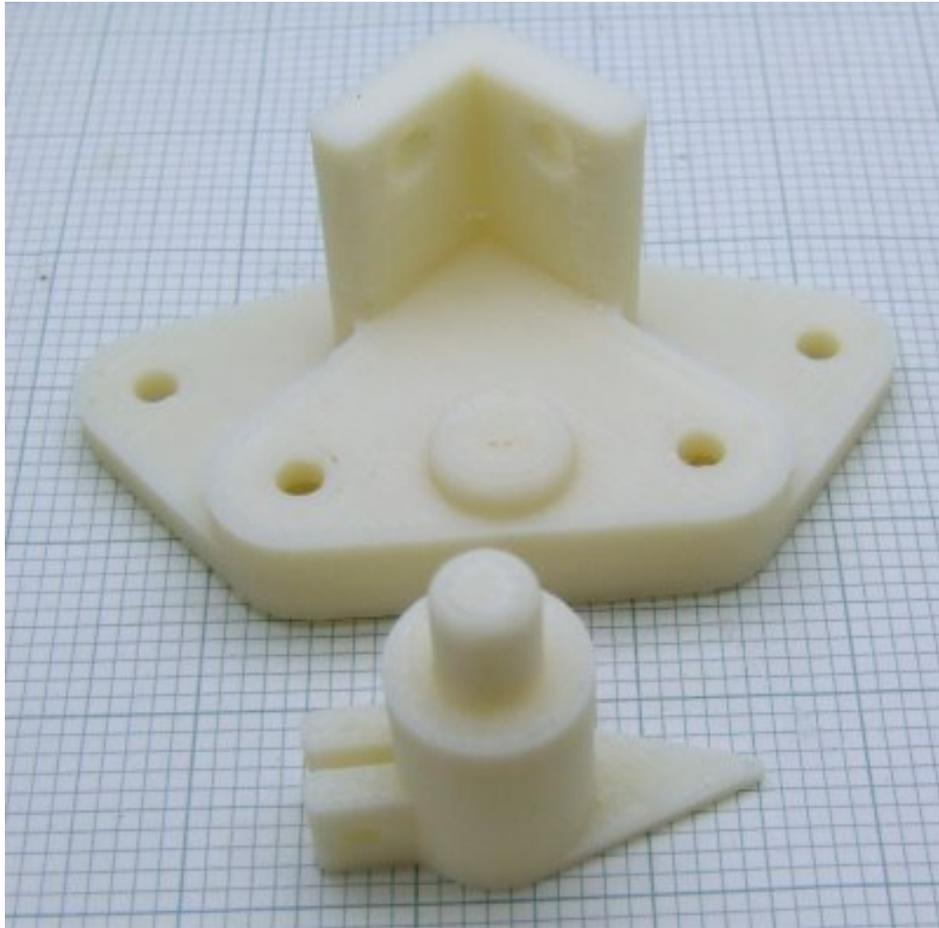
About a year ago I blogged an alternative Z-axis for Darwin using four tin can steppers instead of one expensive stepper and a belt drive. The only thing missing was a source of cheap motors to make it economically viable. Some time ago Forrest Higgs pointed out a source of cheap 15° motors for \$2.50 made by Airpax. I also found them available for \$2 at Surplus Shed. That makes a z-axis for \$8 possible, which is much cheaper than original motor, let alone the belt.

They are surplus stock, so when they are gone they are gone, but there does seem to be a lot of them around. Unfortunately it costs more than \$40 to ship them from the US, so the economics don't look nearly so good this side of the pond.

They are 12V 0.4A per coil, so four wired in parallel will take 1.6A, well within the 2A capability of the RepRap electronics. They are six wire unipolar motors, but they can also be driven from a bipolar drive by using the red and orange wires as one coil and the green and brown as the other.

The pull in rate seems to be about 200pps, which would give  $200 \cdot 15 \cdot 1.25 / 360 = \sim 10$  mm/s with M81.25 threaded rod.

The boss on the back of the motor is a bit bigger than the motors I used before so I have updated the bracket design accordingly. The motors come with a spiral drive screw on the shaft. I could not find a way of getting it off, so I made a new coupling piece that clamps over it. It has a pointer so that it is visually obvious if the motors get out of step with each other.



I have uploaded both of these to [Thingiverse](#). The other parts needed are shown below: -



And this is how they go together: -



# HydraRaptor's second child

Monday, 20th July 2009 by Nophead

Back in March I had a visit from [Marcin Jakubowski](#), the founder of [Open Source Ecology](#). He was over here in Manchester presenting at a conference and asked if he could come and see HydraRaptor, as he wants to use RepRap machines on [Factor e Farm](#). Like RepRap, his project also aims to change the world.

He asked lots of questions and made a couple of videos of my answers for his blog, which you can see [here](#).

I volunteered to print a set of Darwin parts to help get Factor e Farm up and running with 3D printing. I was confident that I would have my Darwin running in time to churn out the parts. However, because I spent a lot of time experimenting with extruder designs in an attempt to get something more reliable, I ran out of time and had to print the parts on HydraRaptor.

Here they are, all 109 of them: -



All the parts were printed with 0.5mm filament at 16mm/s with 32mm/s moves. Most were sliced with Skeinforge set to 25% fill and larger objects have double outlines to maintain strength.

Here are some stats: -

Build time	Plastic volume	Quantity required	Total build time	Total plastic	Weight	Cost	Percentage of total
------------	----------------	-------------------	------------------	---------------	--------	------	---------------------

Corner bracket @ 90%	02:44:44	29.1 cc	8	21:57:49	233.1 cc	291 g	\$5.83	29%
Diagonal tie bracket-chris	00:27:00	4.8 cc	20	09:00:06	96.4 cc	120 g	\$2.41	12%
Bed corner	01:32:06	15.5 cc	4	06:08:25	62.1 cc	78 g	\$1.55	8%
Z-motor-bracket-chris	01:23:12	14.6 cc	4	05:32:47	58.2 cc	73 g	\$1.46	7%
X motor bracket	03:56:35	37.2 cc	1	03:56:35	37.2 cc	46 g	\$0.93	5%
X-carriage	03:51:39	40.2 cc	1	03:51:39	40.2 cc	50 g	\$1.00	5%
Y housing	00:56:36	9.9 cc	3	02:49:47	29.8 cc	37 g	\$0.74	4%
Extruder drive block	02:30:44	26.5 cc	1	02:30:44	26.5 cc	33 g	\$0.66	3%
X idler bracket	02:28:06	25.4 cc	1	02:28:06	25.4 cc	32 g	\$0.64	3%
Y motor bracket	01:51:06	19.6 cc	1	01:51:06	19.6 cc	25 g	\$0.49	2%
Bed constraint	00:43:20	7.5 cc	2	01:26:39	15.1 cc	19 g	\$0.38	2%
Bed clamp	00:21:39	3.7 cc	4	01:26:36	14.7 cc	18 g	\$0.37	2%
Extruder base	01:13:19	13.1 cc	1	01:13:19	13.1 cc	16 g	\$0.33	2%
Z-coupler-airpax	00:14:21	2.6 cc	4	00:57:26	10.2 cc	13 g	\$0.26	1%

Opto bracket @ 50%	00:19:0 0	3.1 cc	3	00:56:5 9	9.4 cc	12 g	\$0.23	1%
X-belt- clamp	00:10:4 6	1.9 cc	5	00:53:5 0	9.5 cc	12 g	\$0.24	1%
Wiper- diagona l- bracket	00:43:5 0	7.6 cc	1	00:43:5 0	7.6 cc	9 g	\$0.19	1%
Wiper- brace	00:13:2 4	2.3 cc	3	00:40:1 1	6.9 cc	9 g	\$0.17	1%
X- constrai nt- bracket	00:38:1 0	6.6 cc	1	00:38:1 0	6.6 cc	8 g	\$0.17	1%
Pulley	00:12:3 5	2.2 cc	3	00:37:4 4	6.7 cc	8 g	\$0.17	1%
Bolt plug	00:04:3 6	0.8 cc	7	00:32:1 1	5.8 cc	7 g	\$0.14	1%
Tall foot	00:14:2 7	2.6 cc	2	00:28:5 4	5.3 cc	7 g	\$0.13	1%
Y motor couplin g	00:25:0 2	4.5 cc	1	00:25:0 2	4.5 cc	6 g	\$0.11	1%
Z- adjuster - housing	00:24:1 2	4.1 cc	1	00:24:1 2	4.1 cc	5 g	\$0.10	1%
Short foot	00:11:2 1	2.1 cc	2	00:22:4 2	4.2 cc	5 g	\$0.10	1%
Fan base	00:22:2 9	4.0 cc	1	00:22:2 9	4.0 cc	5 g	\$0.10	1%
Y belt clamp	00:03:4 3	0.7 cc	4	00:14:5 0	2.6 cc	3 g	\$0.07	0%
Fan-leg	00:15:4 8	2.8 cc	1	00:15:4 8	2.8 cc	4 g	\$0.07	0%

X-motor washer	00:15:27	2.8 cc	1	00:15:27	2.8 cc	3 g	\$0.07	0%	
Z-flag-slider	00:13:00	2.3 cc	1	00:13:00	2.3 cc	3 g	\$0.06	0%	
Bearing 360 run	00:02:47	0.5 cc	4	00:11:09	2.0 cc	3 g	\$0.05	0%	HDPE
Extruder PCB holder	00:09:45	1.7 cc	1	00:09:45	1.7 cc	2 g	\$0.04	0%	
Z-opto-flag	00:08:45	1.6 cc	1	00:08:45	1.6 cc	2 g	\$0.04	0%	Black ABS
X-carriage bearing	00:08:39	1.1 cc	1	00:08:39	1.1 cc	1 g	\$0.03	0%	HDPE
Y-opto-flag	00:07:43	1.4 cc	1	00:07:43	1.4 cc	2 g	\$0.03	0%	Black ABS
Bearing 360 jam	00:02:49	0.5 cc	2	00:05:38	1.0 cc	1 g	\$0.03	0%	Black ABS
X-opto-flag	00:04:43	0.8 cc	1	00:04:43	0.8 cc	1 g	\$0.02	0%	Black ABS
Wiper-lever	00:04:26	0.7 cc	1	00:04:26	0.7 cc	1 g	\$0.02	0%	
Z-flag-clamp	00:03:20	0.6 cc	1	00:03:20	0.6 cc	1 g	\$0.01	0%	
Circlip	00:01:26	0.3 cc	2	00:02:53	0.5 cc	1 g	\$0.01	0%	
Bearing 180-x	00:02:38	0.5 cc	1	00:02:38	0.5 cc	1 g	\$0.01	0%	HDPE
Bearing 180-z	00:02:03	0.4 cc	1	00:02:03	0.4 cc	0 g	\$0.01	0%	ABS
			109	74:28:04	778 cc	973 g	\$19.47	100.00%	

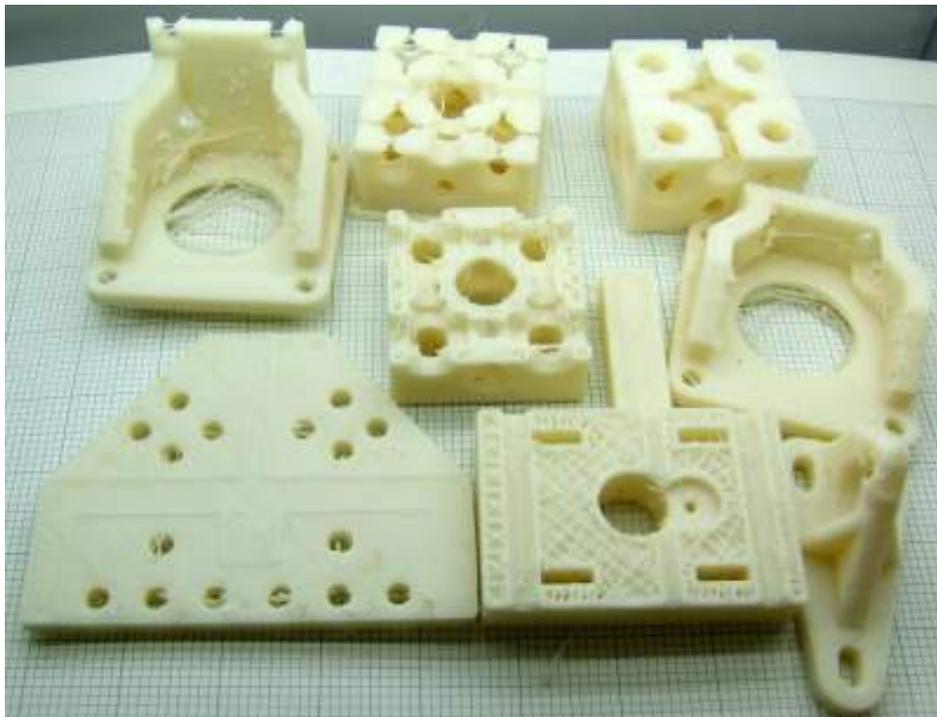
The times and weights are calculated, and don't include the raft time, which is significant, or the time waiting for temperature changes and raft cooling. I weighed the parts on kitchen scales and

they came out at 931g, so pretty close to the calculation. The cost shown is on the basis of ABS at \$20 / Kg.

I save all the rafts for the day when we get recycling working. I weighed them in at ~ 200g, that is about 20% wastage and will bring the actual printing time up to about 100 hours.



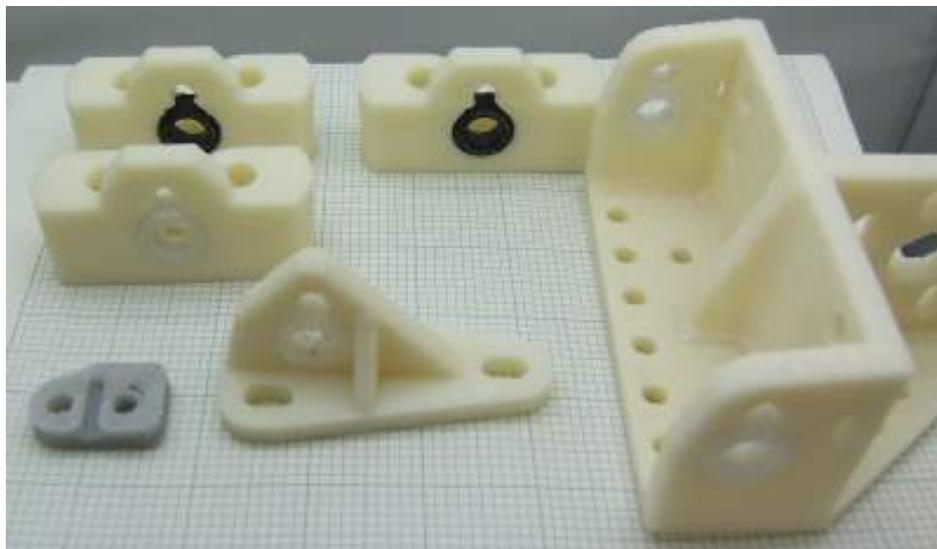
I also wasted 150g in failed prints, for silly reasons, more on that later. It gives a measure of the reliability I am achieving at the moment, i.e. 8 parts failed out of 117 prints so 93% success rate. Of course the bigger the part is, the more chance something will go wrong, so by weight and time it is much worse .



I used plain ABS for most of the parts because it seems to bond better than coloured. I used black

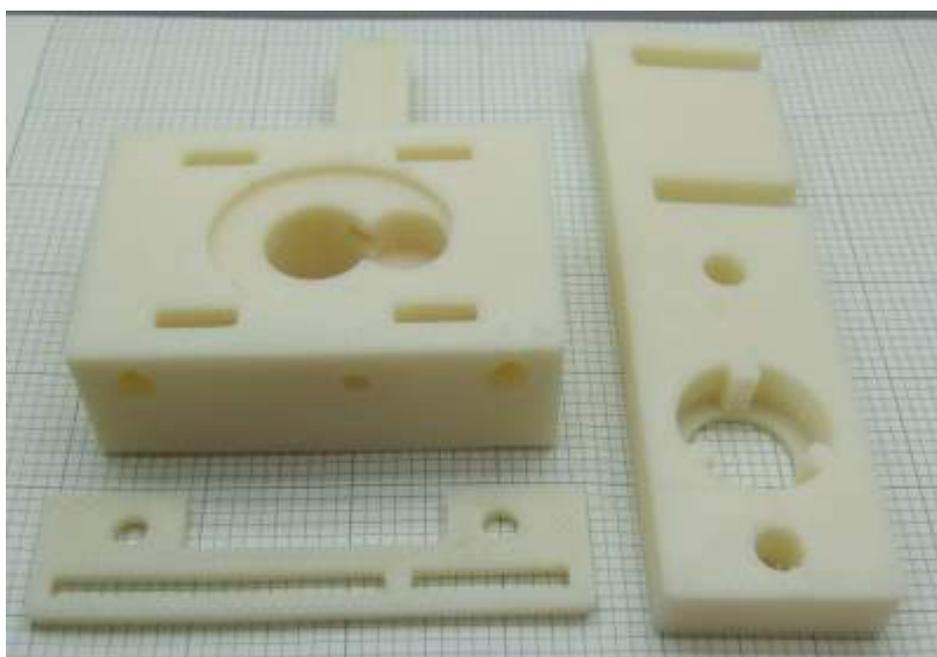
for the opto tabs. No guarantee that they will be opaque to IR, but I think black ABS usually is. The green parts are just ones I had left over from experiments.

I made some of the bearings in HDPE as that should be a better bearing material than ABS, lower friction and longer lasting. The black ones are "jam" bearings so I left them in ABS as they want maximum friction.



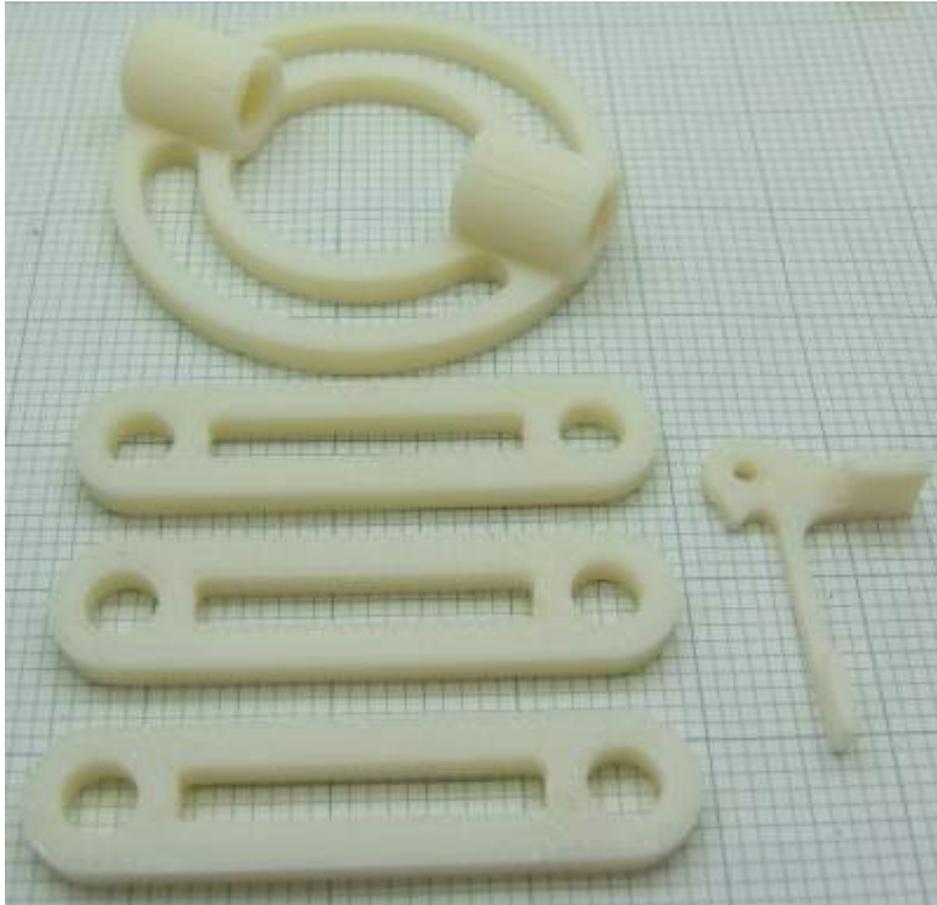
Some of the parts are my own design. Most significant are the z-axis parts described in the previous post. Here is a list of the other design tweaks, with links to the article describing them:- [simplified diagonal tie brackets](#), [X-motor washer](#), [x-carriage bearing](#) and the [feet](#).

Some parts I had never printed before. The Pinch wheel extruder: -

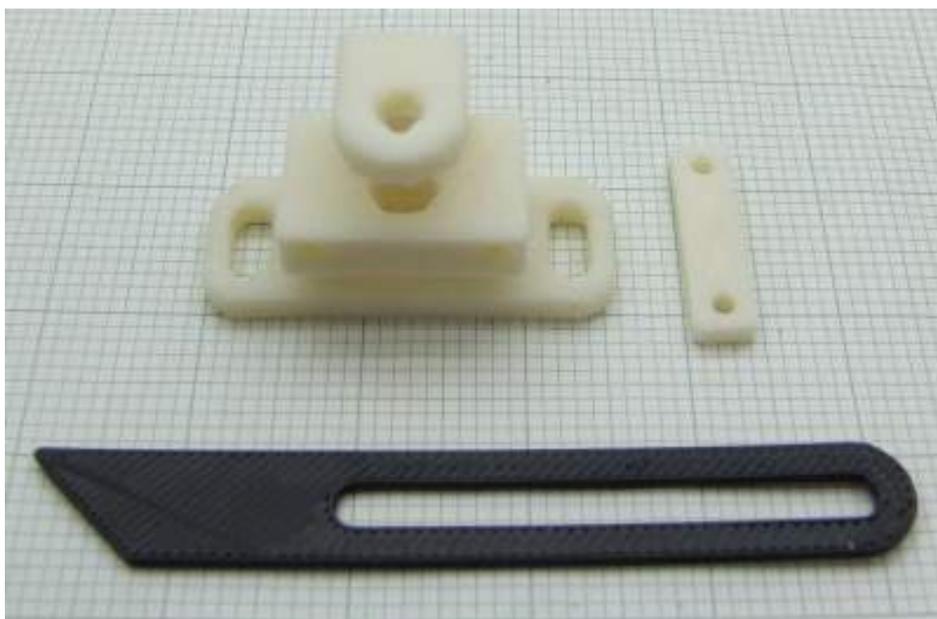


The nozzle wiper assembly has appeared in the latest Darwin release but I can't find any

assembly instructions. I leave it as a puzzle for Edward Miller, the guy who is actually going to build this machine.



Similarly the new adjustable z-opto flag assembly: -



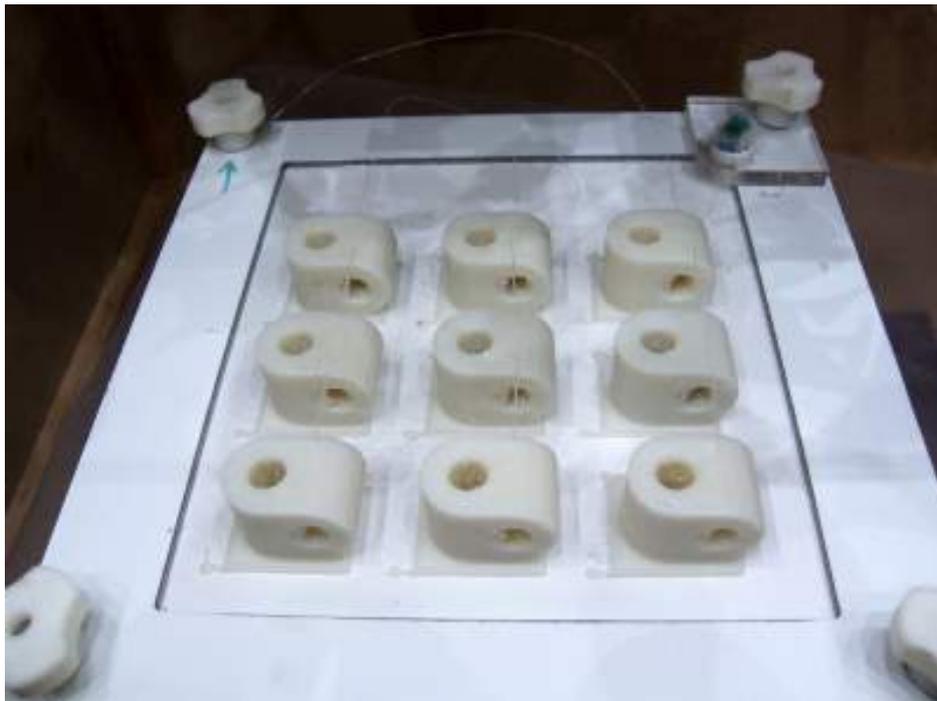
I aimed to print these parts over the course of a week, three batches a day, but the machine had other plans and it actually took me two weeks. I will give more details tomorrow.

# Production issues

Tuesday, 21st July 2009 by Nophead

Since the beginning of the year HydraRaptor has been fairly reliable. I optimistically thought that I could get the 100 hours of printing done in a week. I set one build off before I go to bed and another before I set off for work. I use these slots to print the large parts, in multiples if possible. I use the evenings and weekends to print the many smaller parts while I am around to remove them.

I have a script that can print multiple copies of the same object. It works out how many can fit on the bed and spaces them out so that the head can get in between them. It then prints them, one at a time. I have to remember to tweak the script whenever I change the extruder shape. It simplistically works out the bounding box of the object and then uses the object height to decide how fat the extruder is at that height and spaces the objects so the extruder clears their bounding box. A more sophisticated approach would be to do collision detection between 3D models of the extruder and the object. That would get them a bit closer together in a lot of cases, but I don't consider the gain worth the extra complexity.



I could get a lot more on the bed if all the objects were printed one layer at a time. The easiest way to do that is to load them all into a CAD program, place them like a jigsaw and then join the bases with a very thin membrane that is too thin to actually print, but makes them into one object so they can be sliced together. The reason I don't do that is that the chance of a breakdown in a build that would take tens of hours, possibly days, is too high at the moment. Also, if it did go wrong it could waste a lot of plastic. The objects would also end up with a lot more string on them as the extruder has to flit between them on every layer. Perhaps when the system is more reliable, and ooze

control is better, I will switch to this approach.

Right from the start things did not go to plan and in the end it took two weeks to complete the build and used almost all of my free time during those two weeks. Not something I would choose to do again until I can get it much less labour intensive.

The first time I made these parts the extruder kept breaking due to parts wearing out: the flexible drive cable, the JB-Weld, the 6V GM3 motor, the PTFE barrel and the bearings. Having eliminated all those causes, the breakdowns were more due to human error and bad luck.

This is the extruder I used: -



A recurring problem I had was the extruder jamming due to the heatsink getting too hot, allowing the plastic to melt inside causing the plug effect I have detailed before. It can then no longer be pushed forward, so I have to remove the pump parts and pull it backwards while it is hot.

I have disassembled it and reassembled it so many times that the M3 threaded rods started to lose their threads. I keep meaning to make a wider extruder with M5 bolts but never get round to it. Once the extruder has broken you can't print new parts so you have to fix it some other way, then you don't need the new parts! I should really keep a spare working extruder.

When the threads had stripped, rather than replacing them, I swapped the bottom two wingnuts for threaded brass spacers. They have a much longer thread engagement area, so get round the problem. They are also blind, so they only go on so far. I found with them fully on, I got the right spring tension for ABS using a pair of M4 nuts as spacers. For HDPE I added a second nut each side. Being able to reset the tension consistently each time I put it back together was a big bonus.

The reasons it got too hot were various, but fundamentally it needs a better heatsink or a fan to give more margin between the running temperature and the glass transition of the plastic. The new extruder controller I have built but not tested yet has a second fan drive and a second

thermistor input to allow the cool zone to be regulated. A simpler solution in the case of HydraRaptor would be to make the extruder base / clamp out of aluminium. That would conduct the heat to the z-carriage, which is all aluminium, so could dissipate hundreds of watts .

I eventually tracked down the first reason for over heating to a bad four pin connector in the wires to the heater and thermistor. They are rated at 3A in the Maplin catalogue, but I have had problems with them on the extruder controller before and I am only putting 2A through them. The connections go high resistance for no apparent reason. If it is the heater connection then the heater cools down and the connector gets hot. I have had one de-solder itself from the board.

This time the thermistor connection intermittently went high resistance causing a low temperature reading. I also had the extruder motor stop during a build, again it appeared to be due to its connector failing. I don't know why they do this. If I re-seat them then they work for a while and then fail again. Perhaps they are not rated for the number of insertions they have had due to constantly rebuilding the extruder for 2 years! I have built my new controller with Tyco connectors rather than these unbranded ones.

I switched from the 0.3mm nozzle I have been using recently to 0.5mm so that I could use the same g-code I made the first set of parts from. I can do that because I only use the g-code for tool path information. All the machine settings like temperature and feed rate are in my script.

After the nozzle swap, molten plastic started oozing out of the side of the extruder. The bolts which clamp the compression joint had worked themselves loose after many heat cycles. Changing the nozzle broke the seal and let the plastic out. Tightening them again fixed it.

With the older 0.5mm nozzle I had trouble getting its PTFE cover to stay on. This is essential for making the nozzle wipe work and prevents burnt bits of plastic getting incorporated into the parts leaving brown marks. I had a daft idea of taping it on with Kapton tape. That did not work, but when putting it on I forgot the thermistor wires round back and broke one off.

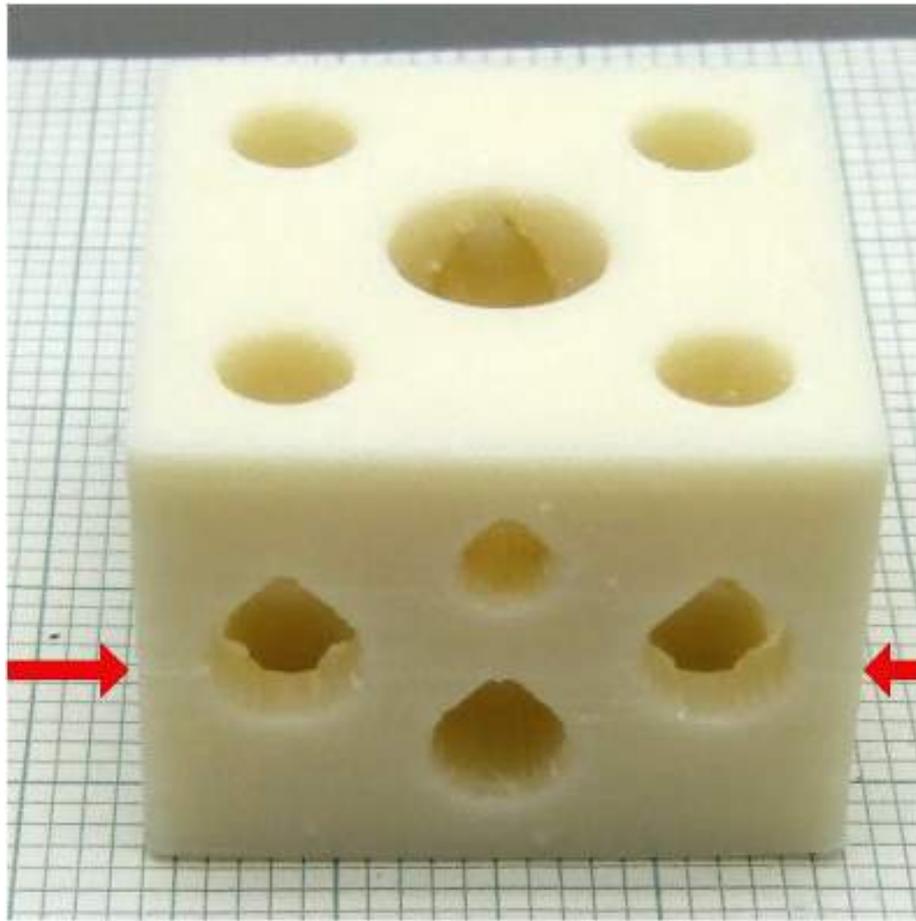
I had to drill another hole and stick a new thermistor in with Cerastil, a 24 hour job. Worse than that I must have mixed the Cerastil with too little water because it started to come out a day later. Because it was out of sight I did not notice, but the objects started to get very hard to remove from the raft and the raft from the bed. It was only when I broke a hole in the surface of the bed that I realised. So another 24 hours of repairs!

I fixed the PTFE cover with two tiny set screws into indentations in the nozzle.

Other times the heatsink seemed to get too hot for no apparent reason, the hot weather did not help. Generally it failed near the end of a large object, very annoying. In the end I used a mains fan about 1m away to keep the heatsink cool.

Apart from the reliability problems the other issues I had were as follows: -

The corner blocks have hair line cracks through the narrow bits half way up the middle of the vertical edges.



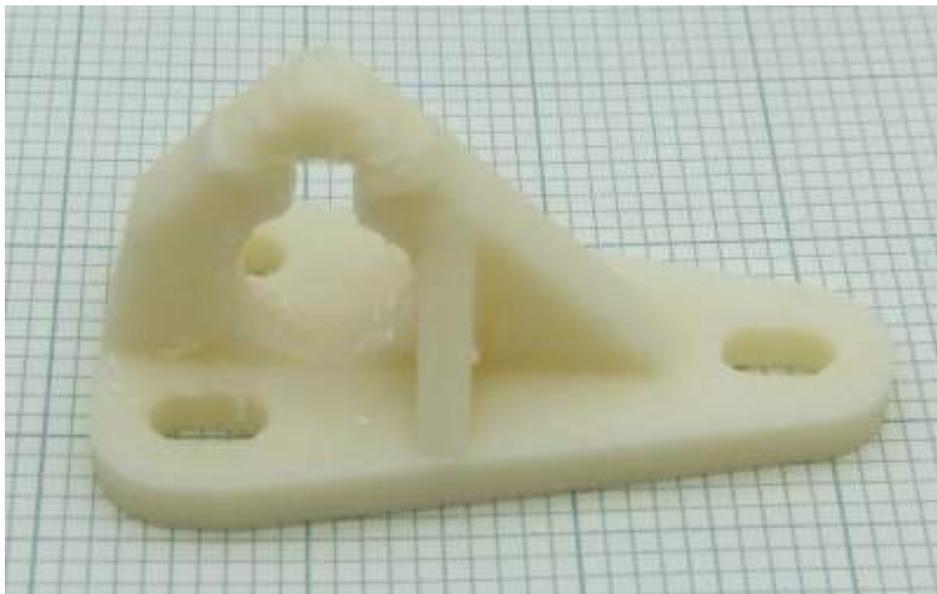
This happened on some of the blocks on my original Darwin and does not seem to matter. I think it was worse this time round because the rafts I used held them down better, leading to less curl up of the bottom corners, so more stress through the edges. I made these with 90% fill, rather than 25%, to ensure they were strong enough. It made absolutely no difference to the cracking but added 8 hours to the print time. It makes the thin bits stronger, but it also increases the warping forces by the same amount.

The rafts I use at the moment are very well bonded. On the up side that reduces warping by holding the object down, but it is quite difficult and time consuming to remove. The only object that pulled away from its raft was the extruder drive block.

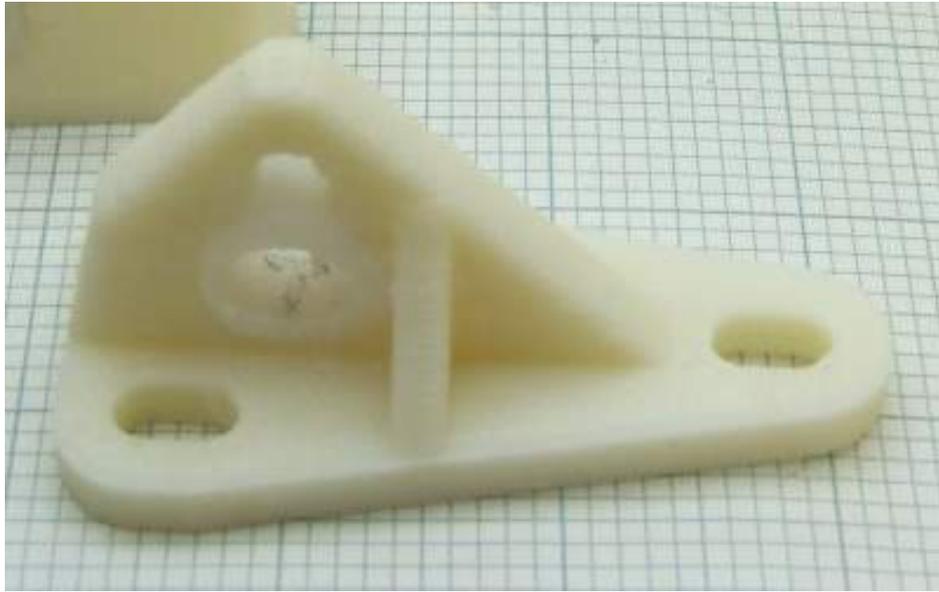


This is the worst case in the set because it is both wide and thick. Fortunately it does not need to be flat.

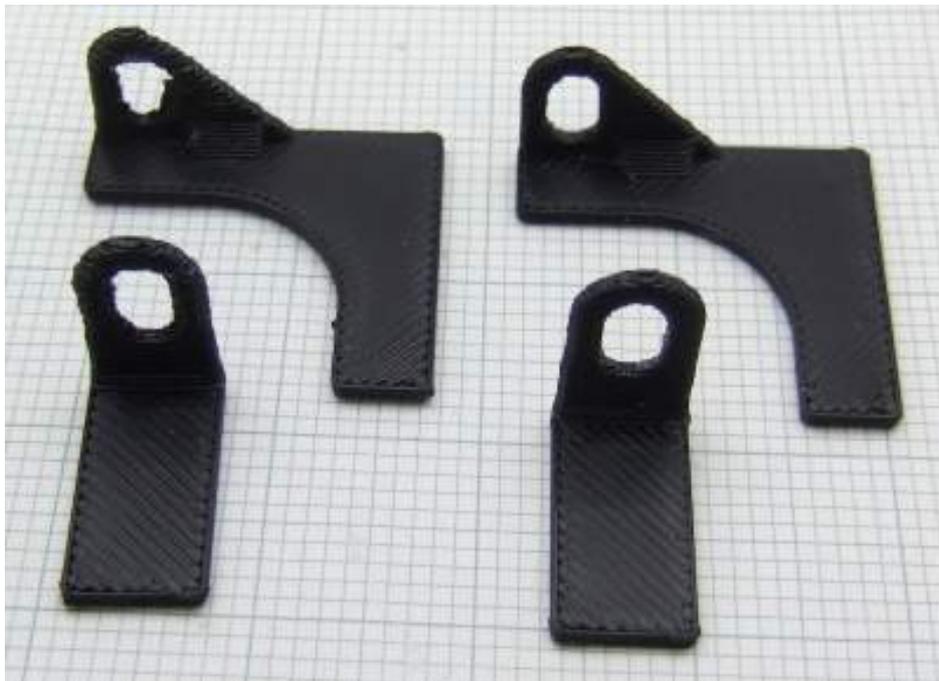
This part came out a bit bockety where it gets thin near the top: -



The problem is the layer is so small it does not have time to cool before the next layer arrives on top. I fixed it by adding some logic which halves the extrusion speed if a layer would take less than 10 seconds at full speed. You can see it completely fixed the problem: -



It was not sufficient for the very thin opto tabs though, so I also cooled them with a fan. Here are the with and without fan versions side by side: -



I won't be printing another set until I get my own Darwin up and running. I hope to double the extrusion speed and reduce the ooze with a stepper driven extruder. The bed is much bigger so perhaps it will only need two batches taking about 1 day each.

# Thoughts on rafts

Wednesday, 22nd July 2009 by Nophead

Erik asked me for details of how I do the rafts so here are my thoughts.

I am not totally happy with the way they are currently and keep fiddling about with them. At the moment they hold well and give a good flat surface on the bottom of the object, but they can be difficult to remove. I use a blunt penknife to remove them.



I use the long blade to remove the raft from the bed and the object. The smaller blade is handy for clearing out strings from internal areas.

It needs to be not too sharp otherwise it tends to cut into the object, or the bed, rather than prizing them apart, or scraping off strings.

I have developed a thick callous on my thumb while making the Darwin parts, and I frequently stab myself, another reason for not having it too sharp!

I think most people use more sparse rafts than I do. They will be easier to remove, but I find that gives a ribbed base on the object.

My rafts are orthogonal to the axes and the infill is at 45°. I find that convenient because you can tell where the raft ends and the object begins.

The bed I use for ABS is, I think, Foamex PVC foam board. It is a solid dense foam 3mm thick, not the type that is soft foam laminated with paper. I glue it to a piece of wooden floor laminate with Evostick contact glue. Now that Evostick has gone solvent free / water based I find it takes much longer to dry than it states on the tin. Blowing it with a gentle breeze from a fan makes it dry much faster.

Even when it is glued down, I find the warping force is strong enough to lift the edges, so I have a frame around the edge that is screwed down. The foam board is reusable over and over again. I only have to replace it when I have had an accident that makes the raft impossible to remove (head too low, or temperature too high).

Other people have reported good results with Acrylic sheets and of course an ABS sheet will work. I have yet to try these. For HDPE I use a PE-LLD chopping board from Ikea that is 10mm thick.

I find that I need at least three raft layers. I.e. each of the three layers has a definite function.

The first layer of the raft has to stick well to the bed but still be peelable. It also has to be thick enough to cope with bumps and troughs that develop on the bed with use and slight errors in the z-calibration.

The filament diameter I use for the base layer is twice the nozzle diameter or 0.8mm, whichever is the biggest. The height of the head is 0.7 times that. The pitch of the zigzag is 3 times the diameter. The head is relatively low, so that it gives a wide filament pressed against the bed. It is widely spaced so that when the bed has a bump it can spread further without merging. It is extruded at the maximum rate that the extruder will do, which works out at only 4mm/s with 1mm filament through a 0.5mm nozzle. The temperature is 225°C for ABS and 215°C for HDPE. The other layers of the raft are extruded at 240°C to bond strongly to the layer below.

The middle layer's function is to give the raft some strength and bridge the ridges created by the bottom layer. The filament diameter is 1.5 times the nozzle aperture. The height of the nozzle above the layer below is again 0.7 times the nozzle. The pitch is 1.2 times the diameter, so that gives closely packed threads that tend to merge.

The top layer aims to present a flat platform to the object but still be discrete threads so they can be picked off one by one. The diameter is the same as the nozzle and the height is 0.8 times that. The pitch is 1.8 times the diameter.

The raft is cooled back to room temperature with a fan before the object is placed on it. The first layer outline of the object is done at half the normal speed (8mm/s for ABS, 4mm/s for HDPE) and at a temperature of 215°C for ABS and 230°C for HDPE. The first layer infill is done at full speed and at 195°C for ABS and 205°C for HDPE. The rest of the object is 240°C.

One annoying thing is that when I peel the raft most of the top layer is left stuck to the object not the middle layer. This is despite the fact that it was bonded to the middle layer at a high temperature, and to the object with a low temperature. I think the reason is that the contact area is 100% against the bottom of the object, but the top of the middle layer is quite wavy so has less contact area. I think adding another dense layer between the middle and the top will fix that, but waste more time and plastic. It is on my very long list of things to try.

As Erik suggested, small objects do not need to be bonded as strongly to the raft as large objects. Something else I mean to try is some logic like this: -

If the length or the width is  $> 30\text{mm}$  and the height  $> 5\text{mm}$  then use a strong raft else a weaker one.

# Lessons from the A3977

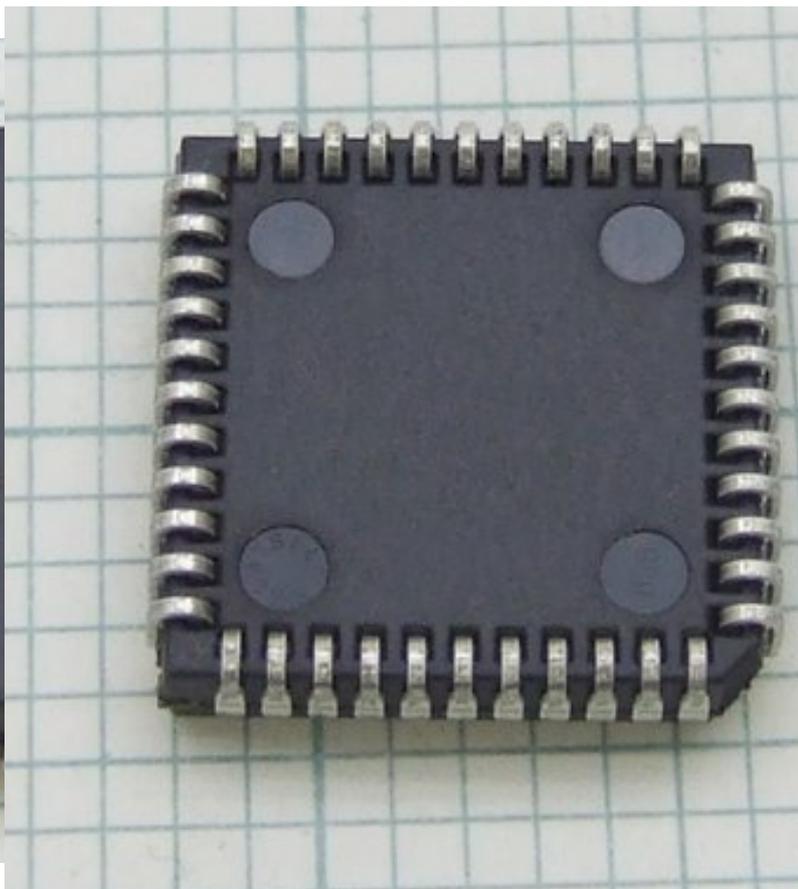
Thursday, 30th July 2009 by Nophead

Having established that I want to move to a stepper driven extruder I set about designing a new extruder controller for HydraRaptor. I fancied using one of the Allegro micro-stepping chopper drivers.

With these chips there are a few things you can adjust by changing component values, like the off time, minimum on time and percentage fast decay. The data sheet explains what they do and gives the formulas but it's not obvious what you should set them to for a particular motor.

Not having any previous experience with Allegro drivers I decided I needed to knock up an evaluation circuit. Fortuitously Zach had sent me some PCBs a long time ago that were his first version of the Stepper Motor Driver v2.0. They used the PLCC version of the A3977.

PLCC packages were a bit of a halfway house between through hole and surface mount. They have leads which come out of the side and then curl underneath.



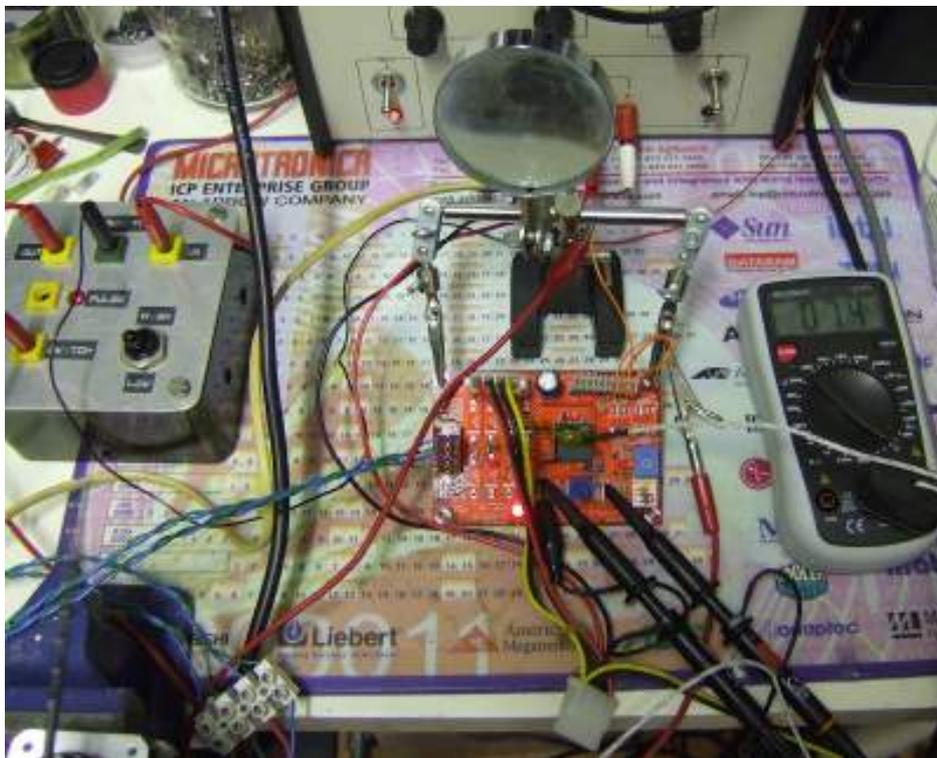
They are handy for programmable devices because you can either surface mount them or put them in sockets (which can be either SMT or through hole). The problem with them in this application is that using a socket is not recommended for current and heat dissipation reasons.

That makes the package a worst of both worlds solution. It is big and bulky like through hole parts but still difficult to hand solder because the pins are underneath. The surface mount version of the A3977 is a fine pitch (0.65mm) TSSOP with a heat slug underneath, so again not easy to solder by hand, it really needs to be done by the solder paste and oven / hotplate method.

Zach moved to the A3982 on subsequent versions, which is easy to hand solder because it is in a SOIC package with 1.27mm pitch. It also has a lower external component count. The down side is that it does not do micro stepping and is only 2A rather than 2.5A. I will probably use the A3983 (which is like the A3982 plus micro stepping and in a TSSOP package).

I managed to hand solder the PLCC at my second attempt. My first attempt had a short, which damaged the chip. I damaged the board removing it (with a cutting disk), so I had to start again on a second PCB. Lots of cursing! The lesson is always to meter a PLCC for shorts before powering up as you can't see shorts underneath it.

Here is my test lash up: -



I can set the step rate with a signal generator, vary the supply voltage from 8 to 35V, see the temperature of the chip and look at the current waveform on a scope .

The initial results were disappointing due to a couple of problems: -

The first was that the chopping occasionally had glitches in it. With the motor stationary I could hear it clicking, and with a scope I could see some cycles shorter than they should be. It got worse with higher supply voltages. At low speeds it did not make much difference, but it did lower the maximum speed. I tracked it down to a lack of high frequency decoupling on the 12V rail. I added a 220nF de-coupler close to the chip and the problem went away. Adding it further from the chip

actually made it worse.

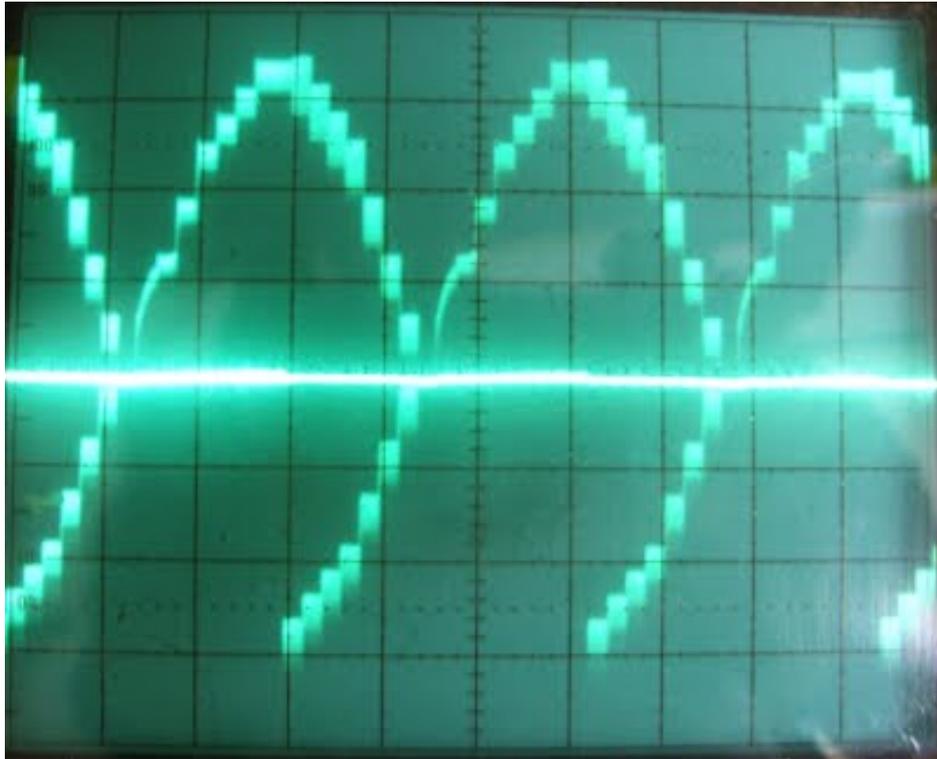
The next problem was that the microstepping was very uneven. I had noticed that same effect with the z-axis of my Darwin using the \$800 microstepping drivers (that I got cheap) that I use on HydraRaptor. At the time I put it down to the small, large step angle tin can motors I was using at the time not being very linear. When I moved to larger 7.5° tin can motors I still had the same problem, and even with the Keling NEMA23 1.8° motors it did not seem right. This puzzled me because they are very similar to the NEMA23 motors on HydraRaptor, which work well with the same drivers. The shaft encoders have the same resolution as the 10 microstepping and they are always spot on or one count out, so pretty linear.

With the A3977 it is easy to get an idea of the current waveform of the motor by measuring the voltage on the sense resistors. It should be a stepped sine wave like this: -



Regardless of which way the coil is energised, the current flows to ground through the sense resistor, so the waveform looks like a full wave rectified sine wave. The current only flows in the sense resistor when the chopper is in the on state though. In the off state the current is circulating through the coil and the bottom two transistors of the H-bridge, so the current in the resistor is zero. That is why there is a bright line along the X-axis. On the falling edge of the wave you can see the sense current goes negative. That is because the chip switches to fast decay mode. When the chopper is in the off state, instead of short circuiting the coil, it reverses the voltage on it, causing the current to flow backwards through the sense resistor onto the supply rail. It only spends part of the switching cycle in fast decay so you see positive current, a lot of zero and some negative current, hence the relative brightness of the lines. This is a case where an analogue scope gives you more information than a digital one.

Initially the waveform looked like this, it was somewhat distorted: -



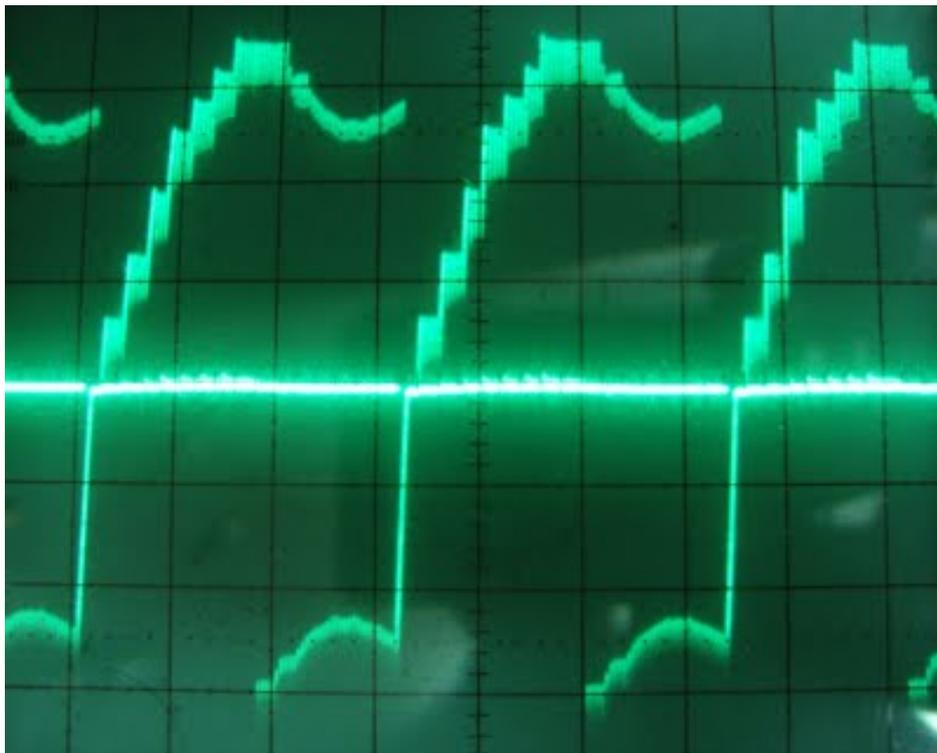
The current rises too quickly at the start of the waveform. The chopper has a constant off time (20uS in this case) and varies the current by changing the on time simply by turning it on until it reaches the target value. But, there is a minimum on time of about 1.4uS, called the blanking period. During that time it ignores the current sense signal to avoid false readings due to ringing on the switching waveform. That means there is a minimum mark space ratio of 1.4 : 21.4 in this case. That sets a minimum current, which also depends on the ratio of the supply voltage to the motor voltage. If this minimum current is more than the lowest microstep value (19.5% of the peak for 1/8 steps) then you get a distorted waveform as above, and the steps are uneven.

To fix it you can lower the supply voltage, raise the current setting or increase the off time. The latter reduces the chopping frequency. If it is below about 15 kHz it will be audible when the motor is stationary. It can also start to beat with the stepping frequency when running at high speeds, particularly when micro stepping, as the step rate is n times faster.

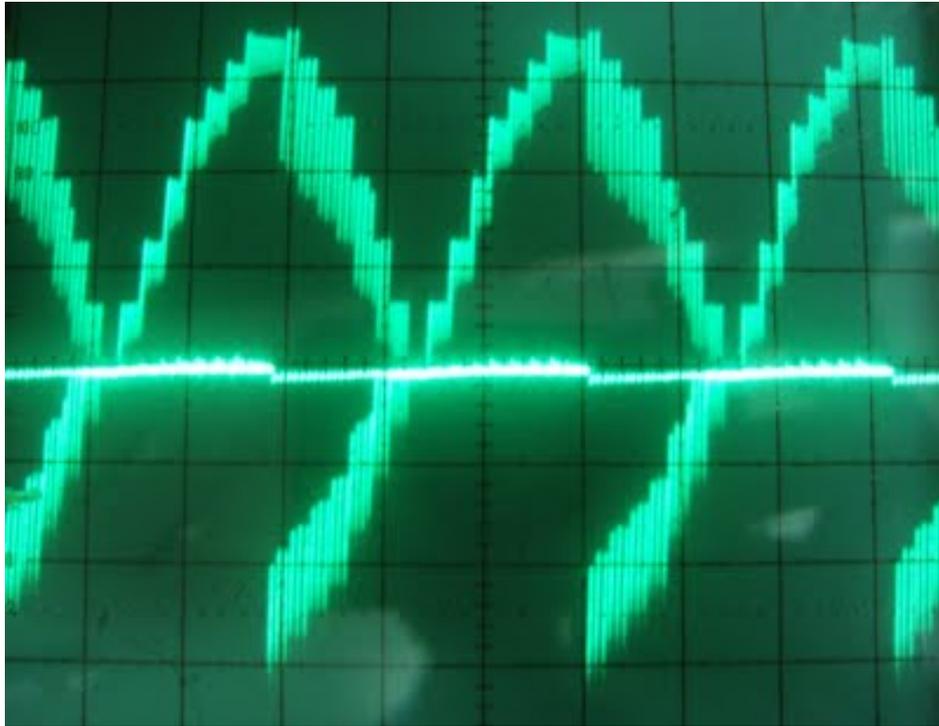
This form of distortion is analogous to crossover distortion on a class B audio amp. You can also get the equivalent of clipping if you use a high voltage motor on a low supply voltage. If the current setting is set to a value which is more than the motor will draw when connected to the supply, then the top of the waveform is flattened off and again the microsteps will be uneven.



Yet another form of distortion occurs when running at high speed: -



Here the back EMF from the motor acting as a generator is preventing the current from falling fast enough to follow the sine wave. This can be fixed by increasing the Percentage of Fast Decay, set by the voltage on the PFD pin. If there is too much you get excessive ripple as shown here: -



For a particular speed and motor there is a sweet spot which sounds audibly quieter: -



So setting up a microstepping drive is not straight forward unless you have an oscilloscope. You can tune the PFD by ear though, as this video demonstrates: -

[Tuning PFD from Nop Head on Vimeo.](#)

You can also see the other forms of distortion if you attach a long pointer and step it round slowly.

Another lesson is that you cannot simply just set the current to accommodate different types of motor. You really need to be able change the off time and the PFD as well, especially if you use different supply voltages.

So I solved the mystery of why microstepping does not work well with the expensive drives on my Darwin. They are rated at 7A but I am only using them at 1A, I am also using low voltage motors on a 36V supply. I bet it is a constant off time chopper and the minimum current is too high.

# More PLaying

Tuesday, 4th August 2009 by Nophead

Way back in April last year I tested a sample of PLA and got as far as making a test block with it and establishing that the warping was much less than the other plastics and you don't need a raft. I finally got round to making some objects with it last week.

The first bed material I used was balsa wood. That works well without a raft. The only downside is that when the object is peeled off it takes a few fibers from the wood with it. No big problem for functional objects, but it does spoil the aesthetic appearance a bit. The top and sides of the object are nice and shiny, but the base is cloudy.

I tried MDF, that gives a smoother finish, but I could not get it to stick reliably. Vik suggested 3M blue masking tape, but I didn't have any to hand, so I tried some sticky back plastic instead. That made objects with a nice glossy base but I could not get the outline to stick reliably.



The lid on the left was made on balsa. I think the black flecks are bits of black ABS which was the last plastic I used in the extruder. The one on the right was made on sticky black plastic. It looks much nicer, but on the top right you can see a bit of missing outline.

I also made this screw-able jewelry box, which looks nice in PLA.

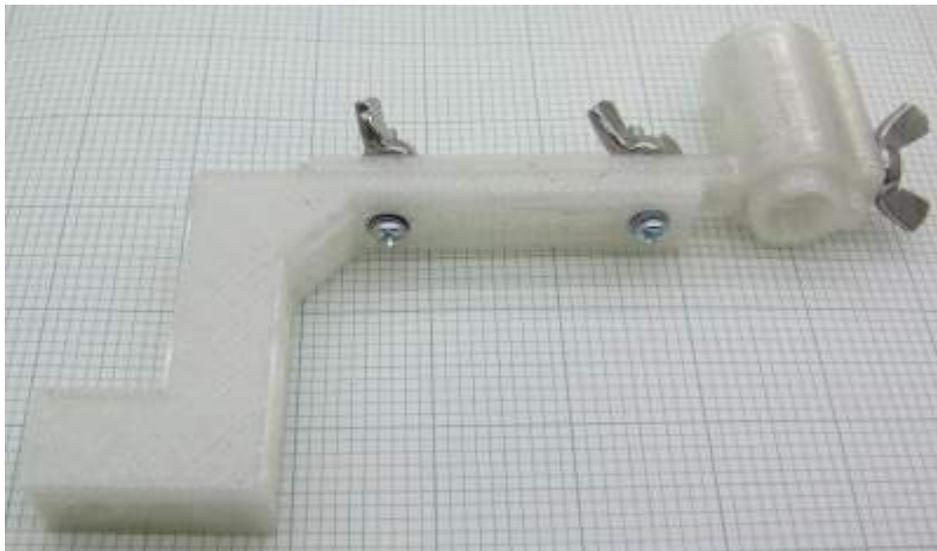


PLA is very nice to extrude. It has a higher melting point than the other plastics but its viscosity falls rapidly with temperature so you can extrude it at lower temperatures. I did the first outline at 210°C, the first layer infill at 200°C and the rest of the object at 180°C. It does not seem critical.

I run the fan after the first layer to make it set quickly. I also needed a fan blowing on the heatsink of my extruder. Otherwise it can heat up past the glass transition of the PLA, which is only about 70°C. When that happens it jams fast and has to be drilled out.

Not needing a raft saves a lot of machine time and also my time removing it.

Even larger objects don't show any warping. I made this contraption to hold a scope probe in place for a job I am doing at work.



Vias are so small nowadays that attaching a wire is difficult and risks ripping the tracks off. Here it is in operation: -



# Motor Maths

Thursday, 6th August 2009 by Nophead

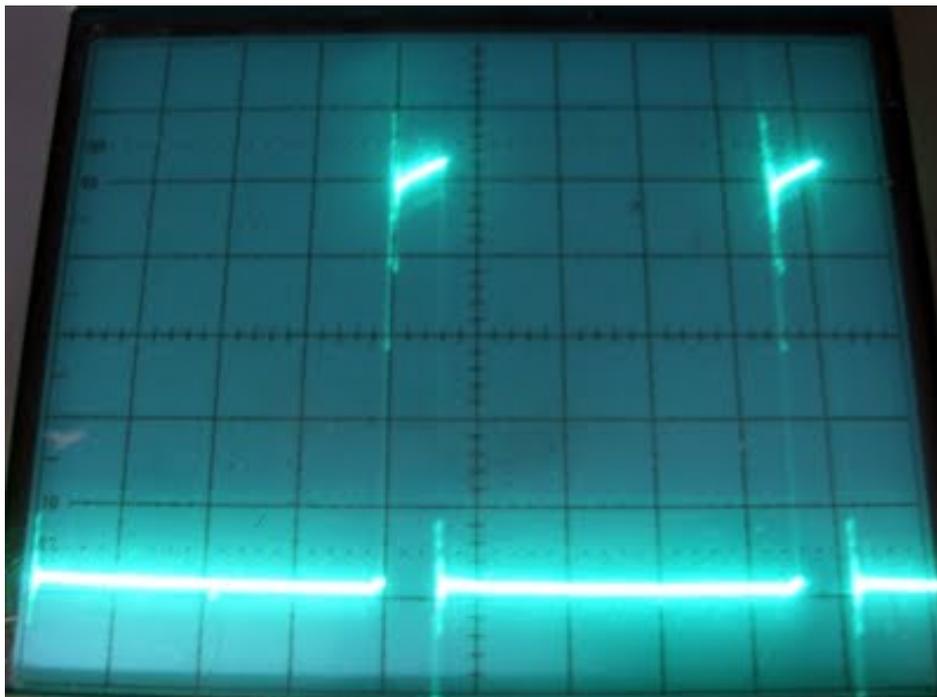
In a [previous post](#) I showed the pitfalls of constant off time choppers like the A3977. Basically you have to set the off time long enough to be able to deliver the lowest current step of the microstepping, otherwise the steps are not equally spaced.

Forrest raised the point of how do you do that without a scope. It is fairly easy to calculate from the target current, supply voltage and motor resistance using nothing more complex than Ohm's law. It did take me a few days to come up with a formula that matched my measurements, but that was because I was accidentally running the chip without synchronous rectification enabled.

The motor current is equal to the reference voltage divided by 8 times the sense resistor. The maximum sense voltage is 0.5V, so a sensible value for the sense resistors is 0.2  $\Omega$ , giving 2.5A maximum with 4V at the reference pin. My lash up uses two 0.5  $\Omega$  resistors in parallel giving a 2A maximum.

The minimum current required on the first step of the microstep will be  $I \sin(\pi/2n)$ , where n is the number of microsteps. In this case n is 8 so the smallest current step is 19.5% of the full current. To calculate the minimum off time needed we need to be able to work out what the duty cycle will be to get a given current.

Here is what the sense resistor waveform looks like when the current is set to 1A and the motor is stationary. The on period is 3 $\mu$ S and the off period is 20 $\mu$ S. The supply voltage is 12V.



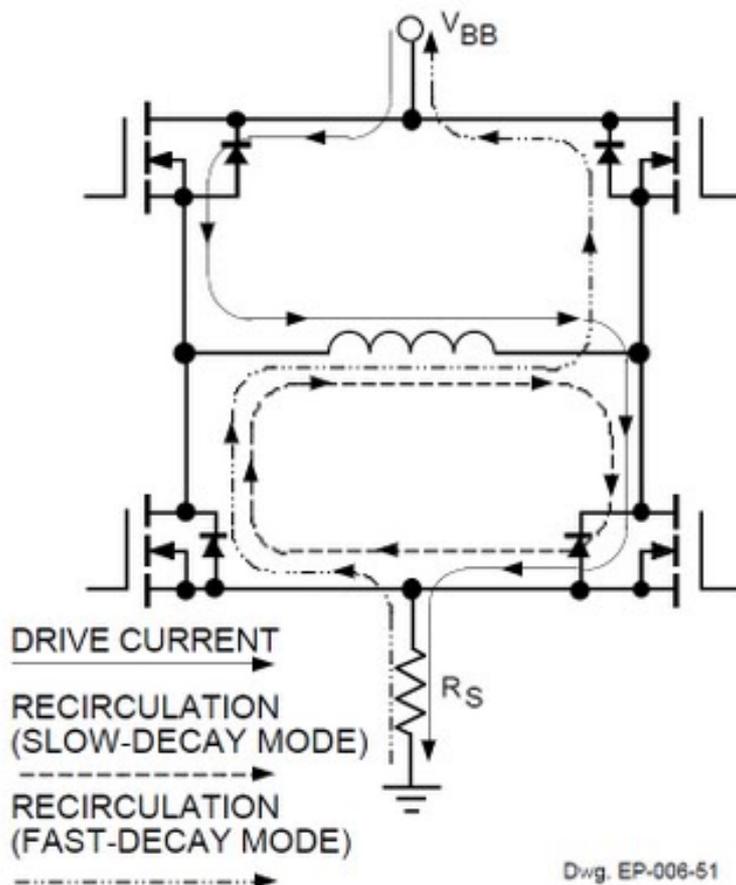
The sloping top of the waveform is actually an exponential curve, but at this scale it is very close to linear and to simplify the calculations I have just used the average value.

So we know that 1A flows from the supply for every 3 out of 23 $\mu$ S. That gives an average current from the supply of  $1A \cdot 3/23 = 130mA$ . Indeed the supply current measures 260mA as there are two coils energised (I set it to full step mode to make this measurement).

When the chopper is on energy flows into the inductance of the motor, increasing its magnetic field slightly. During the off time the current flows in a loop consisting of the motor and the two low side transistors. Power is dissipated by the motor's resistance, so it loses energy by its magnetic field decreasing slightly. We can calculate the duty cycle by reasoning that the energy going in during the on state must equal the energy coming out in the off state.

The motor is a Lin 4118S-62-07 NEMA17 motor I got from Makerbot. It has a coil resistance of only 0.8  $\Omega$ . That means the resistance of the sense resistor and the on resistance of the FETs in the chip are significant in the calculation.

During the on state current flows through one top transistor, the coil, one bottom transistor and the sense resistor. All the resistances convert electricity to heat so the power going into the magnetic field is the power drawn from the supply minus the resistive losses in the circuit.



Power =  $VI$  or  $I^2R$ , Energy =  $PT$ .

So we have  $(V_{supply} - I^2 (R_{motor} + R_{sense} + R_{DS(on) source} + R_{DS(on) sink})) T_{on}$ .

In this example  $(12 - (0.8 + 0.25 + 0.36 + 0.45)) * 3 = 30.4 \mu\text{J}$ .

During the off state the current flows through the motor resistance and two low side transistors, so the energy lost is:  $I^2 (R_{\text{motor}} + 2 R_{\text{DS(on) sink}}) T_{\text{off}}$

In this example  $(0.8 + 2 * 0.36) * 20 = 30.4 \mu\text{J}$ , so theory matches practice (using typical values from the datasheet for  $R_{\text{DS(on)}}$ ), always very satisfying.

So if we call the total resistance in the circuit with the switch on  $R_{\text{on}}$  and the total when it is off  $R_{\text{off}}$  we have: -

$$R_{\text{on}} = R_{\text{motor}} + R_{\text{sense}} + R_{\text{DS(on) source}} + R_{\text{DS(on) sink}} = 1.86$$

$$R_{\text{off}} = R_{\text{motor}} + 2 R_{\text{DS(on) sink}} = 1.52$$

$$\text{Then } T_{\text{off}} = T_{\text{on}} (V/I - R_{\text{on}}) / R_{\text{off}}$$

For our example if we set the minimum  $T_{\text{on}} (T_{\text{blank}})$  to be  $1\mu\text{S}$ ,  $I = 0.195\text{A}$ , so  $T_{\text{off}}$  is  $39\mu\text{S}$ .

At  $1\text{A}$   $T_{\text{on}}$  will then be  $\sim 6\mu\text{S}$ . So the minimum chopping frequency will be  $\sim 22\text{kHz}$  and the maximum will be  $25\text{kHz}$ .

$$C_T = T_{\text{blank}} / 1400 = 714\text{pF}, \text{ so use } 680\text{pF}.$$

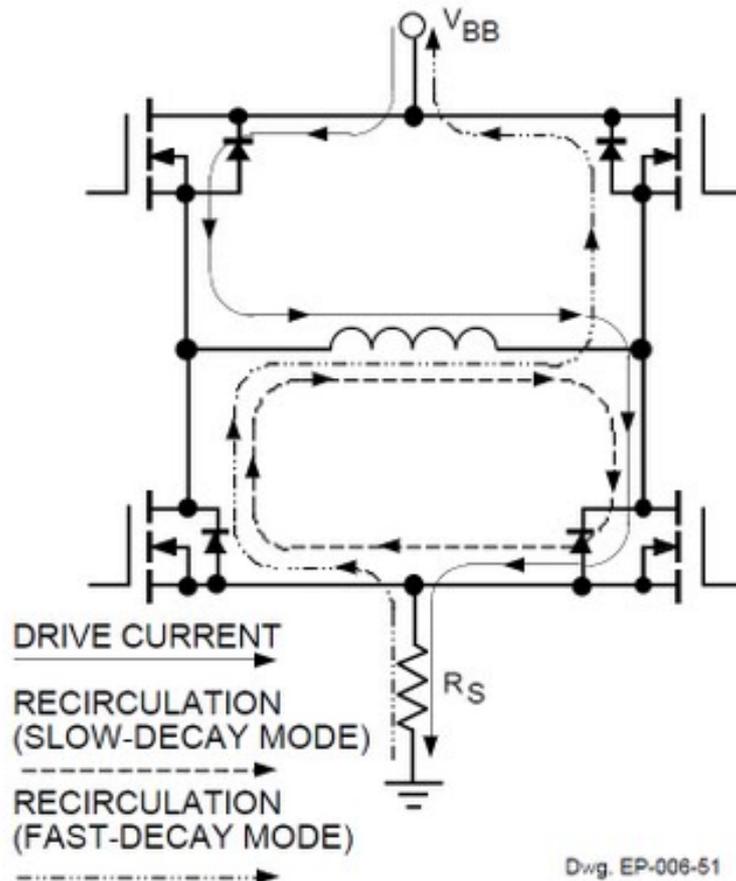
$$R_T = T_{\text{off}} / C_T = 58\text{K}, \text{ so use } 62\text{K}.$$

So in conclusion using the simple formulas above it is easy to calculate the correct values for a given motor, supply voltage and minimum current. I wish the datasheet and apps note had included this formula.

# Mixed decay, mixed blessing

Sunday, 9th August 2009 by Nophead

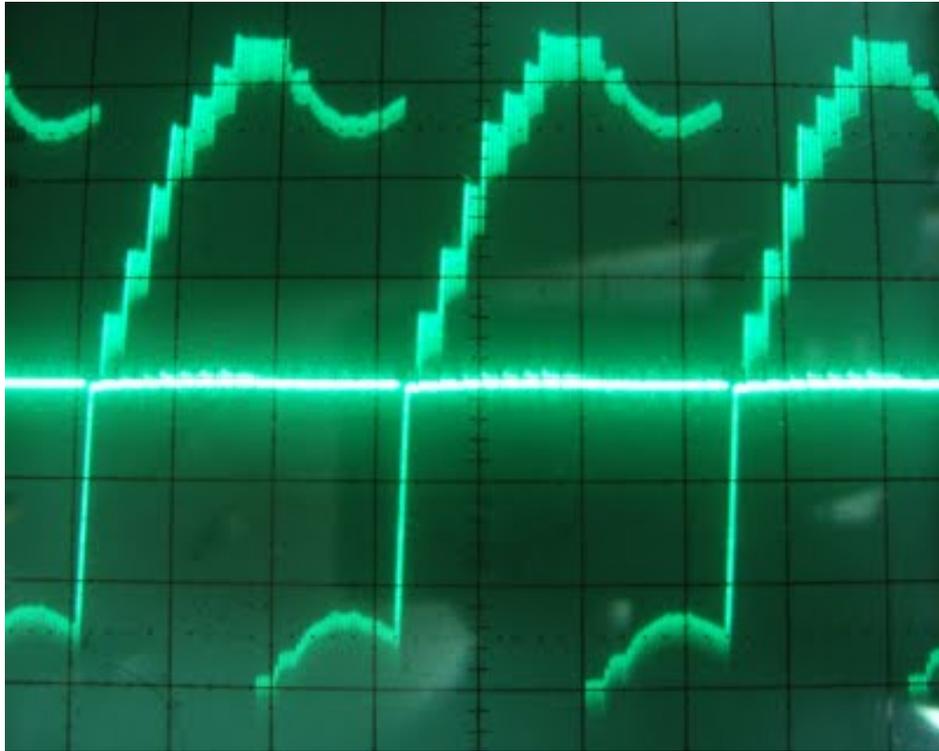
Having set the correct off time to suit my motor I can now micro step it with equal spaced steps, but only if I disable the mixed decay mode.



When the chopper switches off it can do it two ways. It can turn on both low side transistors. That short circuits the motor and lets the current recirculate. If the coil was a perfect inductor and the transistors perfect switches, the current would circulate forever and you would have a superconducting magnet. Real coils and transistors have some resistance, which causes the current to decay, but as these are relatively small the mode is called slow decay.

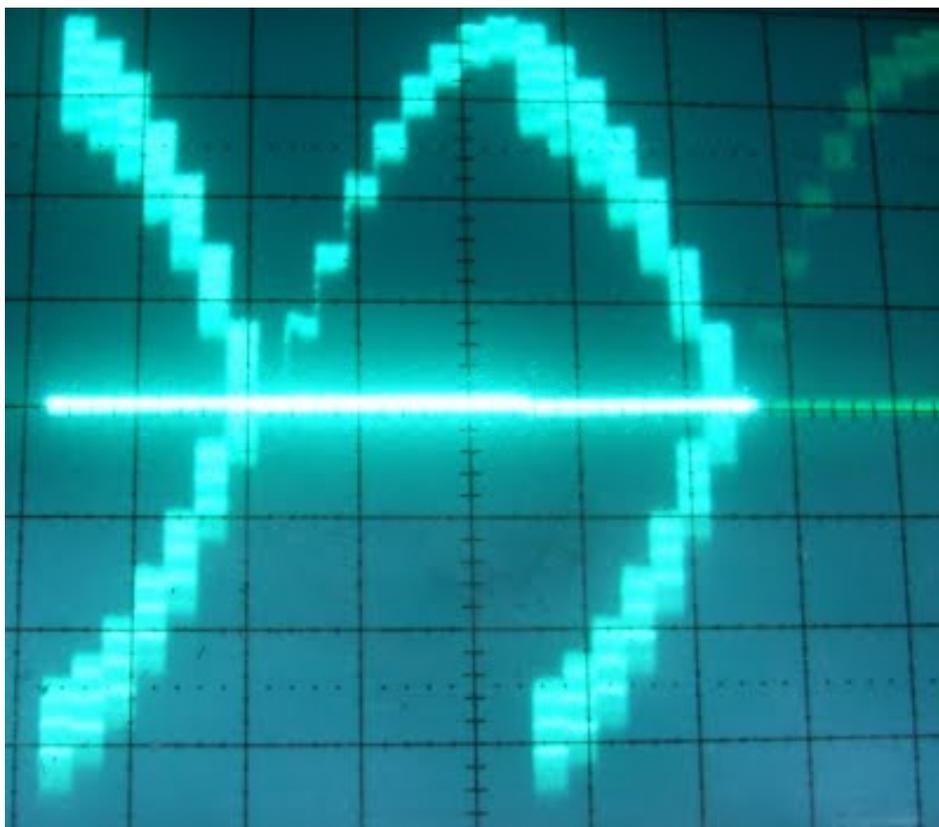
This is fine and efficient until you take the motor's back emf into account. During the rising part of the sine wave the magnet is moving towards the pole piece, so it generates a voltage that causes the current to fall faster. The on time gets longer to compensate and all is well.

On the trailing edge of the sine curve the magnet has gone past the pole piece and generates a voltage that increases the current in the coil. If it is going fast enough it can mean that the current doesn't fall at all during the slow decay period. As I showed previously that can cause a severely distorted waveform which makes the motor noisy.



The Allegro chips offer a mixed decay mode, where they switch to fast decay for part of the chopping cycle on the downward half of the sine curve. In fast decay mode one low side and one high side transistor turn on and reverse the voltage across the motor. That overcomes the BEMF and causes the current to fall much faster. It also returns current to the supply rail, which can upset some power supplies if there isn't some other load to absorb it.

Mixed decay gives a current waveform like this: -



The off time is fixed, so the current falls further making the ripple greater. If you set the percentage fast decay to give a clean waveform at your top speed, then the ripple increases at slower speeds. It is maximum when stationary, when there is no BEMF and fast decay is not required at all.

The problem is that the target current is the trip point of the comparator, so it is the peak of the chopping waveform. That means the average current is less by half the ripple current giving a positional error.

With the low inductance motor I am using, the ripple current has a large amplitude, so the error introduced when the motor is stationary is about the same as a micro step. That means the first step with fast decay is about twice as big as it should be and the last step is virtually zero.

With the A3977 I can disable fast decay and the steps are fairly even, but fast running is then distorted. The PFD setting needs to change with speed.

With the A3983 that I have used on my new extruder controller the PFD setting is fixed at 31.25%. That means I can't get evenly spaced microsteps with the NEMA17's that I have, when running slowly. Not a big problem with the extruder because I plan to gear it down 40:1, which means one micro step is only about 0.02mm. I am only using microstepping to give smooth motion rather than extra resolution.

The problem is exaggerated because not only am I using a low inductance motor, but I am also trying to run it at 1A, whereas it is rated for 2.5A. At 2.5A the off time would be about 2.5 times smaller, so the ripple would be 2.5 times less. The steps in the current waveform would be 2.5 times bigger, so the distortion would be reduced by 6.25 times. As it is about one microstep now, it would reduce to 1/6th of a microstep, so would be acceptable. The temperature rise would then be 6.25 times greater of course.

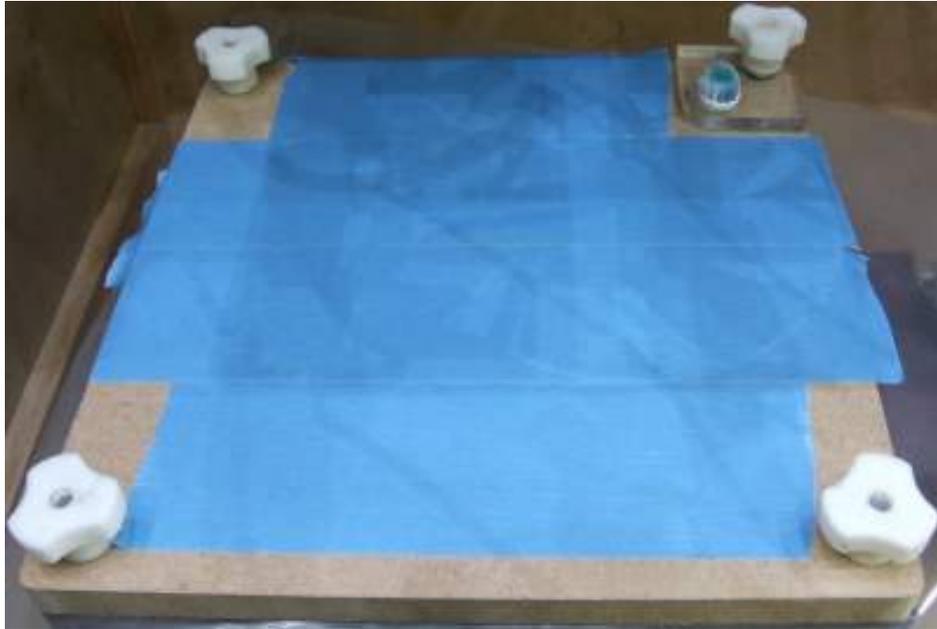
I was planning to use A3977s for my axis control though, where positional accuracy is important. I am beginning to think I will be better off just using dual H-bridges and doing the rest in software using a powerful micro with a fast ADC.

To be able to cope with a wide variety of motors you need to change the current, the off time setting and the percentage of fast decay. You also need to take the ripple current amplitude into account to control the average current, rather than the peak. All these things could be automated with a software solution.

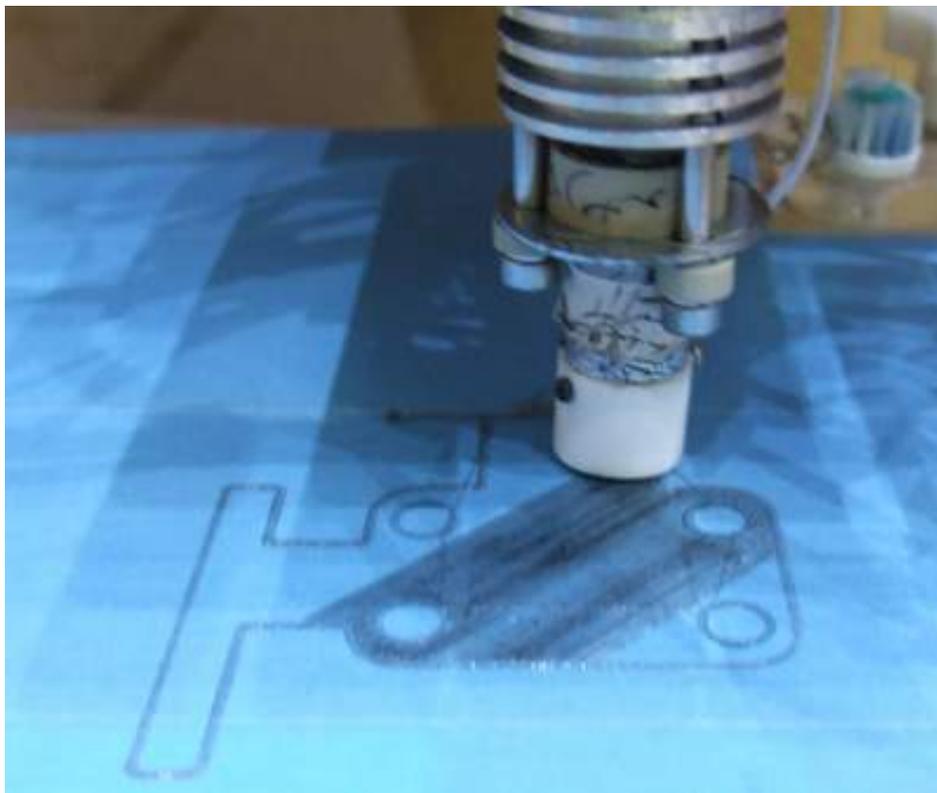
# Black and blue

Sunday, 9th August 2009 by Nophead

I got some of the 3M blue masking tape that Vik Olliver recommended as a bed material for PLA. It seems to be available up to 50mm wide, so four strips covers the bed of my machine.

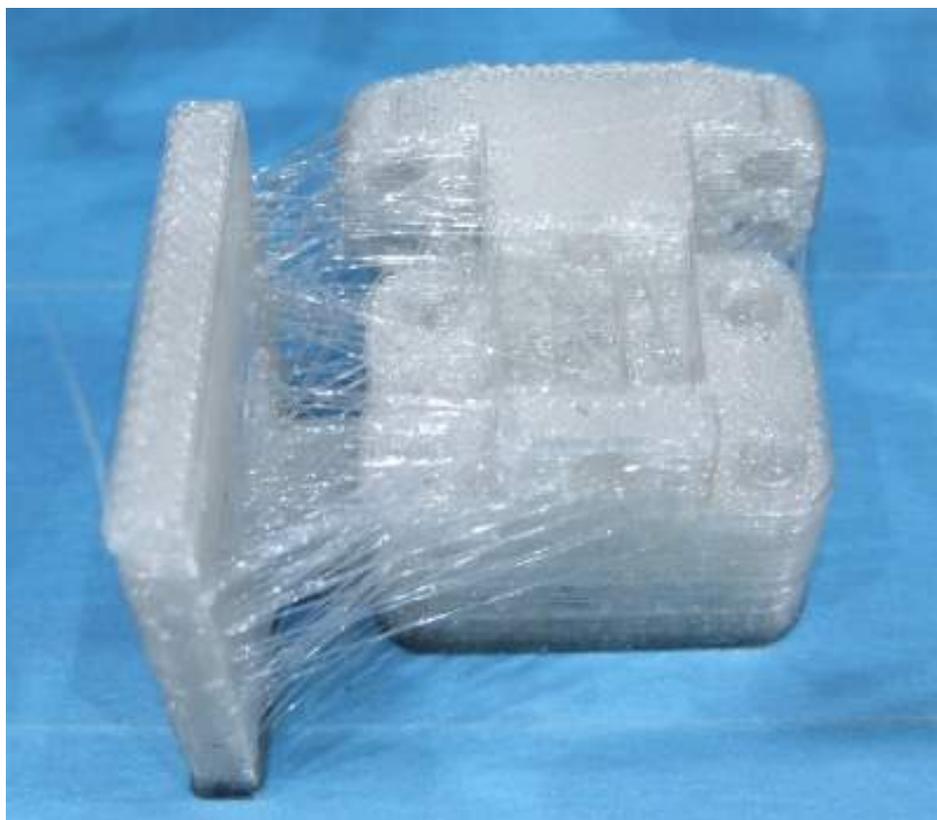


Whereas I could not get PLA to stick reliably to MDF, it sticks easily to the tape.



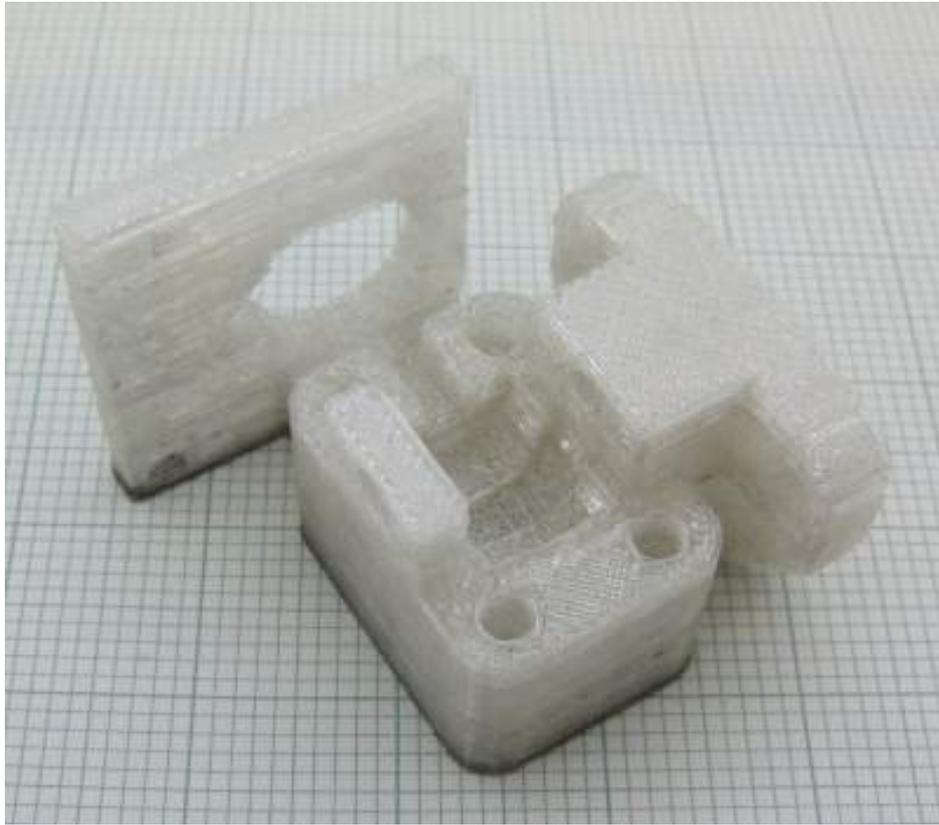
Why is it black? Well my feed of PLA from the overhead hanging basket snapped. It must have got kinked and bent through too sharp a radius. When I pushed the new end into the top of the extruder to restart it, I must have caught some of the grease from the top bearing. The grease is yellow, but as soon as the stainless steel bearings have run for a while it turns black. That small amount of material was enough to turn the first few layers of my object dark grey.

The object was a complicated shape and came out very hairy: -



It took a lot of cleaning up and has some defects and weak spots where there is a lack of material due to the oozing that occurs on the way there. I have some compensation for this effect, which works well for ABS. Basically I estimate the amount of ooze from the time the extruder is off and then run the extruder for a while to replace it before starting a new thread. I think the constants need to be completely different for PLA.

The object was relatively large, but showed no sign of warping, even when removed from the bed. The base of it is completely flat.



I had successfully removed several small objects but I damaged the tape removing this one. It was easy to replace one strip and reducing the temperature of the first layer from 210°C to 180°C seems to allow large objects to be removed easily.

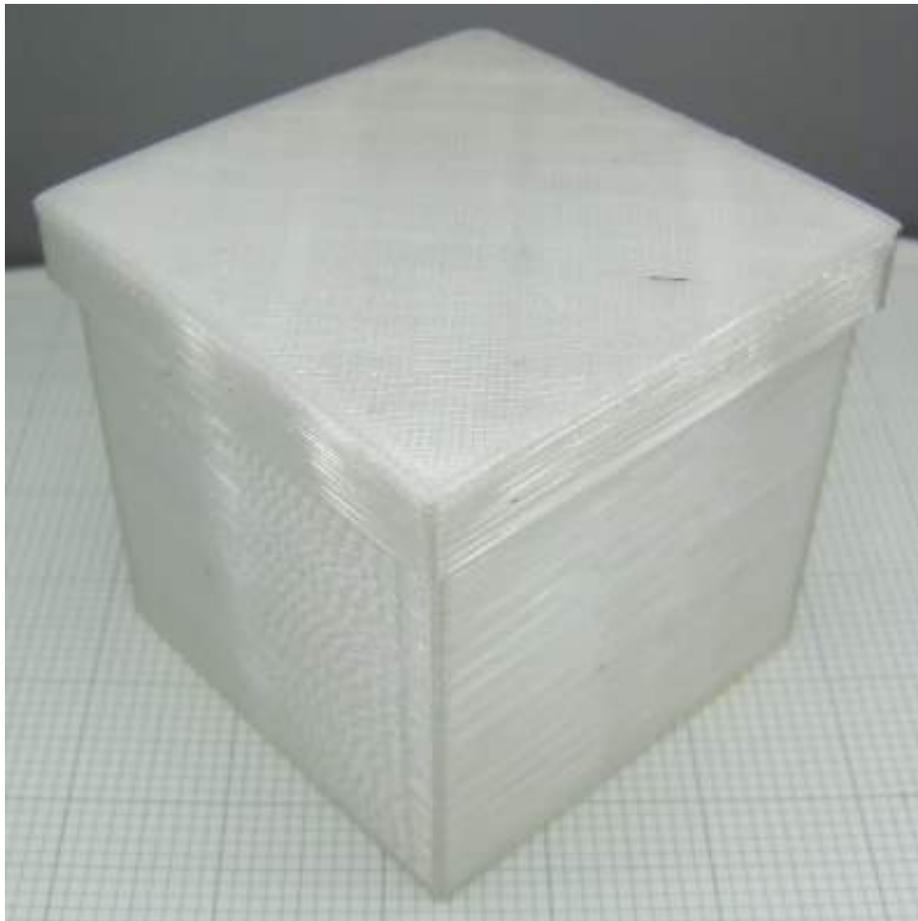


Another problem I had was the PLA started revolving fairly quickly in the extruder, making the hanging basket spin. Each time it revolves it reduces the amount fed by one thread pitch. If it happens too much the object has material missing. I fixed it by applying some oil to a felt washer that the filament passes through. A good reason for moving to a pinch wheel feed though.

I made a 65mm cube shaped box and it showed no sign of lifting from the bed.



It was easy to remove though and this time did not damage the tape. Even after it was removed the base stayed fairly flat.



Much better than my attempt to make the same box in ABS some time ago.



Not only did it curl after it was removed from the base, it also ripped itself open at the corners while it was being built. There is also a wavy distortion on the left face which I had not encountered before.

I think what happened is that when the cracks opened the edges lifted, causing the nozzle to bear down on the wall it had already built. That meant there was excess plastic for the gap between the surface and the nozzle. Normally when that happens blobs are left on the surface. When the next layer is done the nozzle just plows through the blobs. Because the walls are only 1.5mm thick in this case, and tall, they flexed sideways instead. That caused a ripple and the effect seems to build up layer on layer. I could see the wall flexing as the nozzle passed over it.

So PLA allows bigger objects to be made before a heated bed or chamber becomes necessary.

Even relatively large PLA objects can be made without a raft. That saves a lot of time and material, but you do have to get the z-calibration spot on and the bed perfectly level.

The masking tape makes a good, cheap, reusable bed material and it is quick and easy to replace if you do damage it.

# Time for a new extruder controller

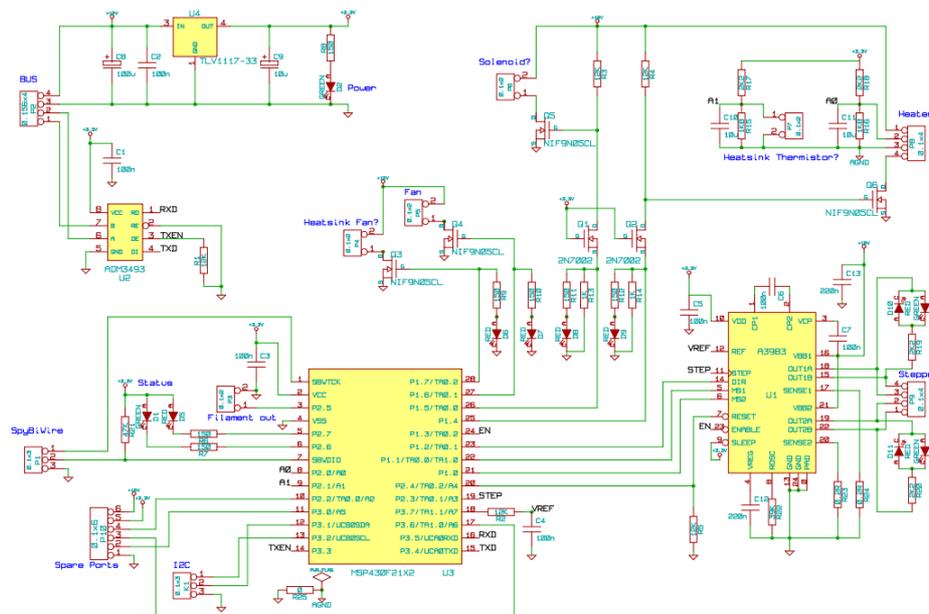
Monday, 24th August 2009 by Nophead

Having decided to switch to stepper drive for my extruder I needed to make a new extruder controller for HydraRaptor, the previous one has served me well for two years.

The spec for the new one is: -

- I<sup>2</sup>C or RS485 comms link to the main controller.
- Micro stepping bipolar stepper drive.
- Heater control from a thermistor.
- Fan control output.
- Second fan control and second thermistor for controlling extruder heatsink temperature.
- A spare output for a solenoid, etc.
- A filament empty input.

I designed it in Kicad and got the PCB made professionally. Here is the schematic: -



U4 generates a local 3.3V rail from the 12V supply. C8 and C9 are the bulk low frequency decoupling for the 12V and 3.3V rails respectively. C1, C2, C3, C5, C7, C12 and C13 are the high frequency decouplers placed close to the chips that they are decoupling. D2 is a green LED to indicate the board is powered.

U2 is an RS485 transceiver which I intend to use on my Darwin. It is slow rate limited and ESD protected but somewhat expensive compared to the older 5V versions. R1 ensures the transmitter is off until the micro takes control of it. HydraRaptor uses I<sup>2</sup>C to talk to its heads, via K1.

Q3, Q4 Q5 and Q6 are NIF9N05CL protected MOSFETs to control fans, heaters and solenoids,

etc. They are protected against over current, over voltage (hence no back EMF diodes), over temperature and ESD. They also have controlled edge rates to minimize RFI. Q1 and Q2, together with R3 and R4, are level translators to increase the gate drive voltage on the two higher current drives. That minimises the on resistance to ensure they stay cool without heatsinks, even at 2A or more. R13 and R14 ensure the drives are off before the micro starts. D6, D7, D8 & D9 are red LEDs to indicate when the outputs are on. Essential for the heater output, but a luxury for the others.

R15, R16, R17 & R18 form the correct potential dividers to give a good approximation to linear temperature response for 10K thermistors, see here for details. For a 100K thermistor they would simply be 10 times bigger. C10 and C11 remove high frequency noise. Probably unnecessary as a little noise actually seems beneficial because it converts bang-bang control to proportional.

The thermistor inputs have their own analogue ground rail, which is only linked to the main ground at one point close to the VSS pin of the MCU. This is done via a zero ohm link, R25, on the schematic. On the PCB this is the smallest footprint available and is shorted by a bit of copper, so no part is actually fitted. The reason for this bodge is to keep the track separate from the ground fill, so that no current from the heater or motors is passing along it. That might cause a small voltage offset that would affect the temperature reading.

U1 is the stepper motor driver. I used the Allegro A3983 as it gives micro stepping with a smaller external part count than the A3977, but as mentioned previously it does have some disadvantages.

C6 and C7 form a charge pump which generates a supply rail for the gate drive that is higher than the main supply voltage (12V). That allows the top transistors of the H-bridges to be N-channel devices, rather than P-channel, which have inferior performance.

R22 sets the off time of the chopper and needs to be different values for different motors as described here.

R23 and R24 are 1W current sense resistors. I found them to be expensive in the 2512 SMT package. It is actually cheaper to use two 1210 0.5W resistors in parallel, or through hole parts mounted vertically, which take up less board area.

The reference voltage for the chopper is generated by a high frequency PWM output on the micro and smoothed to DC by R2 and C4. That allows software control of the motor current. As I had plenty of spare I/O on the micro I also have software control of the step mode (full, half, quarter or eighth), the enable and the reset pin. R5 ensures the stepper is disabled before the micro is running. As with R1 it ensures the circuit is well behaved before the micro is programmed, or when it is being run under a debugger.

D3, D4, D10 and D11 indicate the state of the stepper outputs, a bit of a luxury really. With SMT parts there is not much point in using bi-colour LEDs. It is cheaper to use back to back red and

green next to each other.

I used an MSP430F2012 micro on my first extruder controller because you get a full development kit including an excellent C compiler, in circuit programming and source level debugging for \$20. I think there is also open source support via gcc, but I have not investigated that yet.

For this one I had to move up to an MSP430F2112 to get a UART for the RS485. As it is the same core with different peripherals I assumed my \$20 eZ430 SpyBiWire debugger would still work. Big mistake! It programs OK but it locks up when trying to debug. It also miss-identifies the chip. I have two, and the second one I tried said the firmware needed updating and offered to do it. JUST SAY NO, if you say yes it reprograms the eZ430 and it never talks again. I contacted TI and they have no plans to fix this firmware updating bug so I got an MSP-FET430UIF debugger for \$99. It does JTAG as well as SpyBiWire so I should be able to mend my second eZ430, as it has JTAG test points and I read the security fuse is not blown. I also suspect a new eZ430 may well work as the web page has been updated to show it supports the F21x2 now.

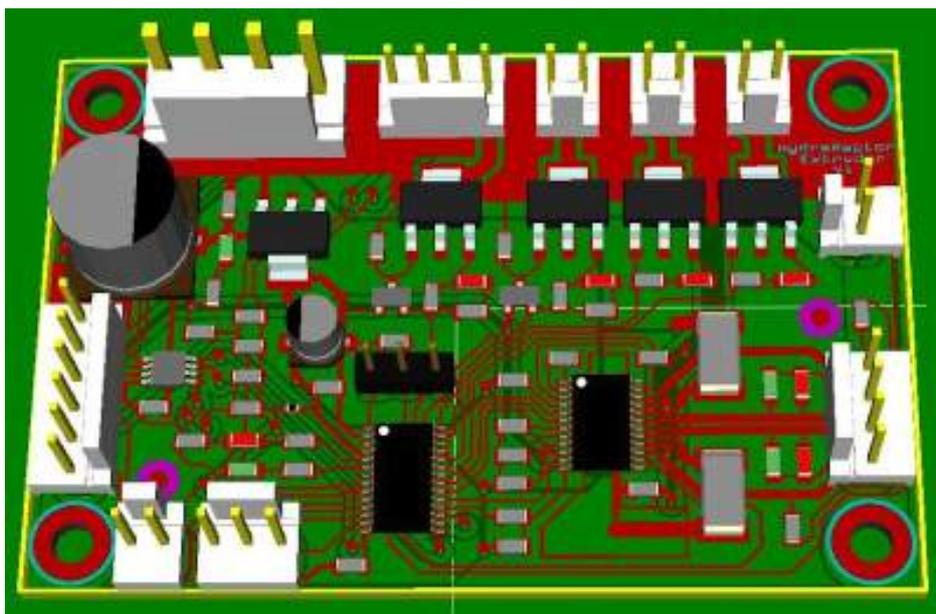
D1 and D5 are red and green status lights. I light the green one to show the processor is running and blink it whenever it receives a command. The red one indicates errors.

P3 is a connector for a filament out switch. I haven't implemented one of those yet as a spool of filament usually lasts many months. It uses an internal pullup resistor to pull it high when the switch is open.

P1 is the SpiBiWire connector for programming and debugging.

Even with extravagant motor control I had three spare I/O lines, so I brought them out to a connector with the supply rails for future expansion.

This is what Kicad predicted the populated board would look like: -



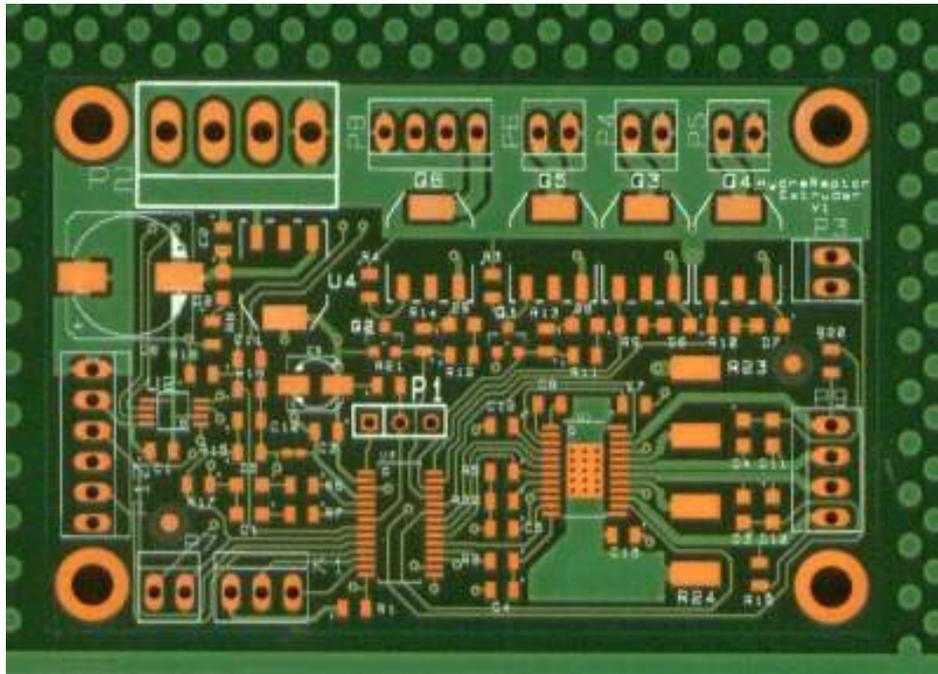
I found 3D models for all the parts on the web but the connectors were a bit of a nightmare. I used Tyco MTA100 and MTA156 connectors as they seem to be about the cheapest form of wire to board connector. As usual there is an expensive tool to insert the wires, but you can get away with using a pair of needle nosed pliers, or even make a tool as it is only a metal plate with slots in it mounted in a plastic handle. We should be able to RepRap one.

Tyco have STEP and IGES 3D models on their website. Kicad needs VRML, which should have been no problem as CoCreate can import STEP or IGES and export VRML. But Kicad did not like the VRML from CoCreate, it seems it has to come from Wings3D. Wings can import STL but it does not like the STL from CoCreate or AOI either. In the end I had to do IGES -> CoCreate -> STL -> AOI -> OBJ -> Wings-> VRML -> Kicad! I coloured the body and pins in Wings.

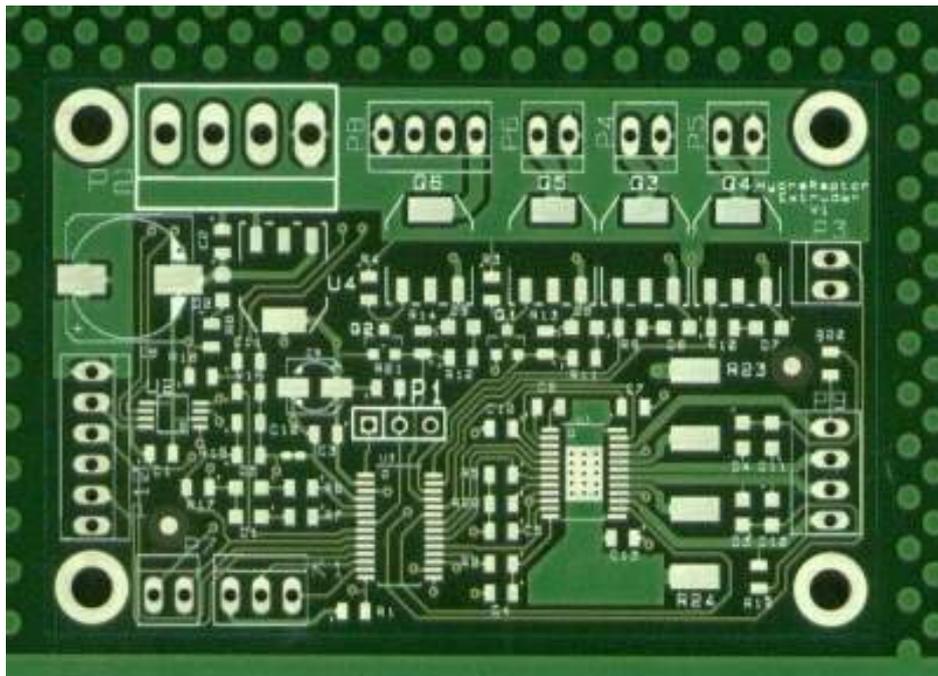
I got five boards made by PCB-Pool in 8 working days for €125 including shipping, certainly not the cheapest, especially as it included Irish VAT at 21.5% (VAT is only 15% at the moment in the UK), but I like the web interface, the quality is good and they include a free solder paste stencil.



They also email pictures of the board being made at five different stages, although two of mine went missing. Here it is before the tin plating was added: -

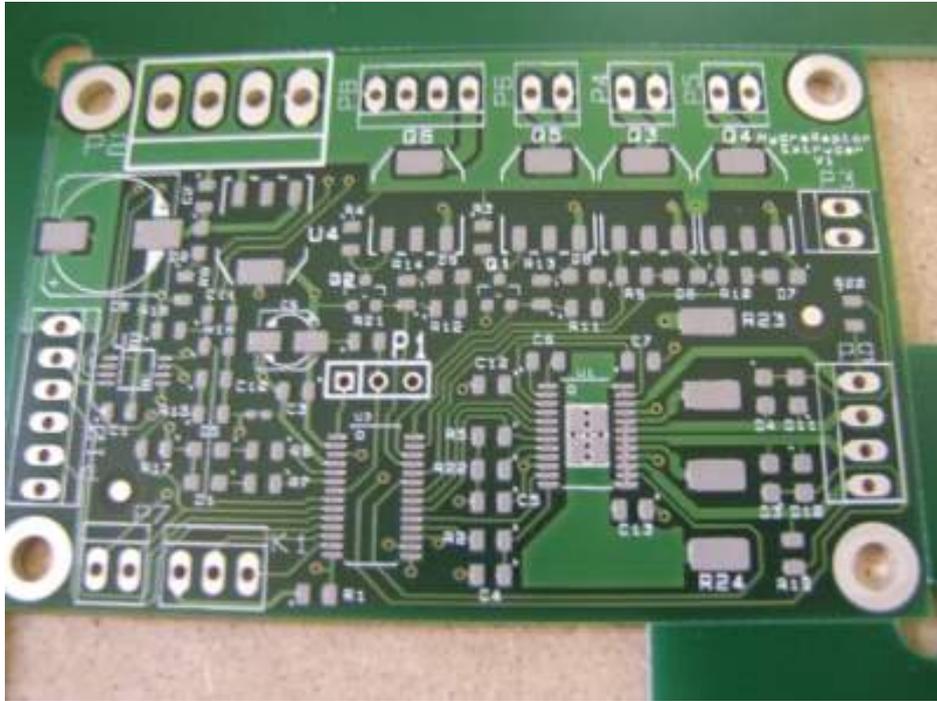


And here it is finished apart from routing the outline: -



Using the stencil is very easy. You trap the board between two L-shaped pieces of PCB material stuck to a flat surface with some masking tape. You then align the stencil over the pads and stick one edge with masking tape. Spread some solder paste along the edge that is stuck and then wipe it across the board with a metal squeegee to force it through the holes and leave it exactly level with the surface of the stencil.

You then lift the stencil carefully from the edge that is not taped down.



Notice how the paste for the heat slug on the A3983 is split into four and reduced in area. This is recommended to stop the chip floating on the paste and sliding across the footprint. It was not easy to do in Kicad. It doesn't seem possible to do it in the component footprint, so I had to draw on the stencil layer of the PCB. That means if I use the chip again I will have to do it again. I had the same limitation when expanding the resist layer around the fiducials. These are the two copper circles bottom left and mid right. They are used for optical alignment of pick and place machines.

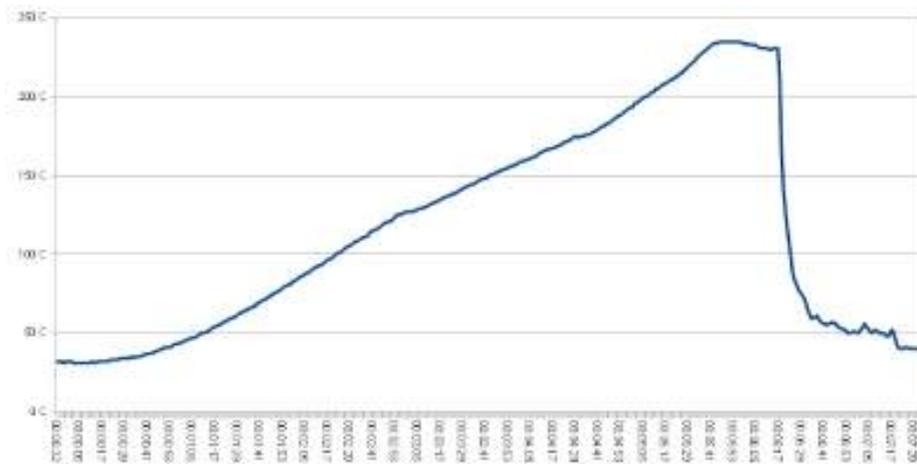
The next stage is to place all the parts with tweezers. I used 0805 footprints for all the passives, so they were not too fiddly to do by hand. I hope to be able to automate the pasting and placement with HydraRaptor soon.

Then I cooked the board in a cheap electric oven, a Severin TO 2020 for €45.



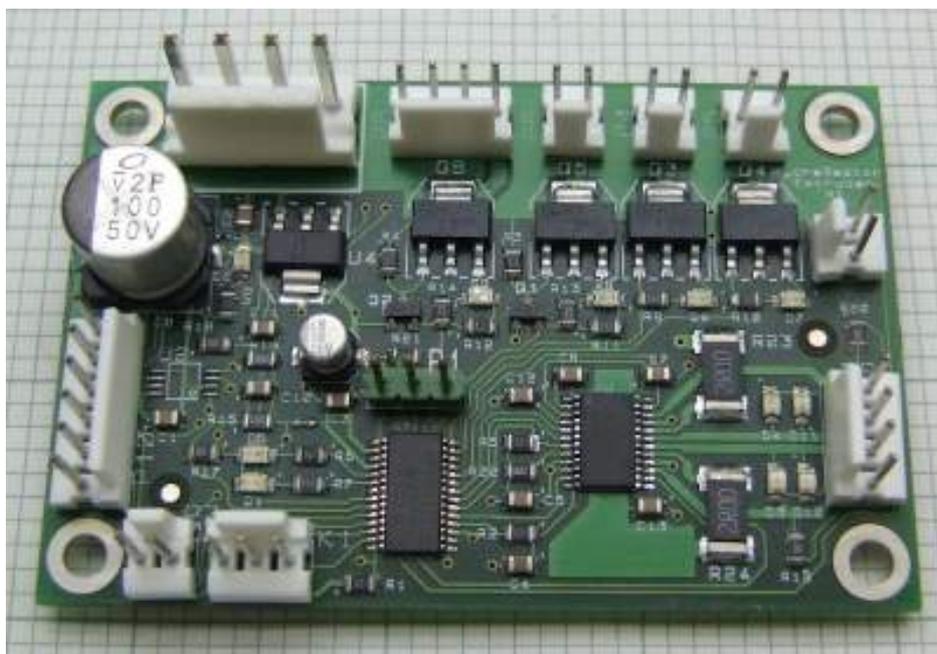
I believe you can get these for as little as £15. I expect they give more even heating than using a hotplate, as they heat from above as well as below, but a hotplate has the advantage of taking up a lot less space and probably uses less power. I will be making a heated bed for HydraRaptor, so I might be able to use that.

The temperature profile was controlled by a thermocouple attached to a PID controller that I borrowed from work.



When I have time I will connect one of Zach's thermocouple boards to a spare analogue input on HydraRaptor and plug the oven into the software controlled mains outlet that HydraRaptor has, and then program it as a PID controller. Not another head, but certainly another manufacturing capability. I will also try putting extruded objects through a heat cycle in the oven while they are still attached to the base. It should release the stress so they don't warp further when removed.

This was the finished result after hand soldering the connectors: -

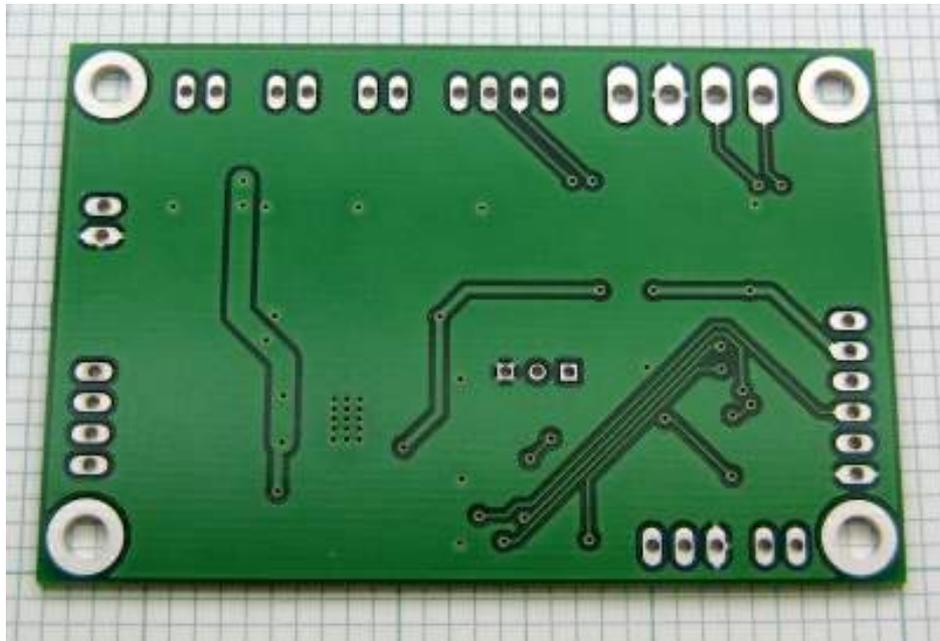


U2 is not fitted because I got the footprint wrong, doh! I can bodge one on when I need RS485. There are two construction faults on this picture, can you spot them?

The reflow was not perfect. The big capacitor did not flow at all. The temperature needs to be a bit higher, or perhaps the warm-up a bit slower. There were solder bridges on the TSSOP chips. That was because you are supposed to shrink the stencil apertures by an amount related to the stencil thickness to get the correct amount of paste. Normally the stencil manufacturer will do that for you but PCB-Pool do not offer it on their free stencils, presumably because they are shared with other designs. Unfortunately Kicad only seems to be able to make them 1:1 with the pads. It is open source, and written in C++, which I know well, so I could have a go at adding that facility if I had the time.

I have tested the board and used it to control one of my experimental extruders, more details tomorrow. The only thing wrong with it apart from the footprint error is that the A3983 gets too hot to deliver its full rated current of 2A. 1A is no problem, which should be plenty for the extruder designs I have in mind.

The back of the board is nearly all copper to give a good heatsink but at 2A per coil the chip will dissipate  $2 \times 2A^2 (0.3 + 0.3) = 4.8W$ . The datasheet recommends a 4 layer board with 2oz copper on the outer layers. I am not sure what the extra cost of 2oz is. I will investigate the heat distribution in more detail at some point.



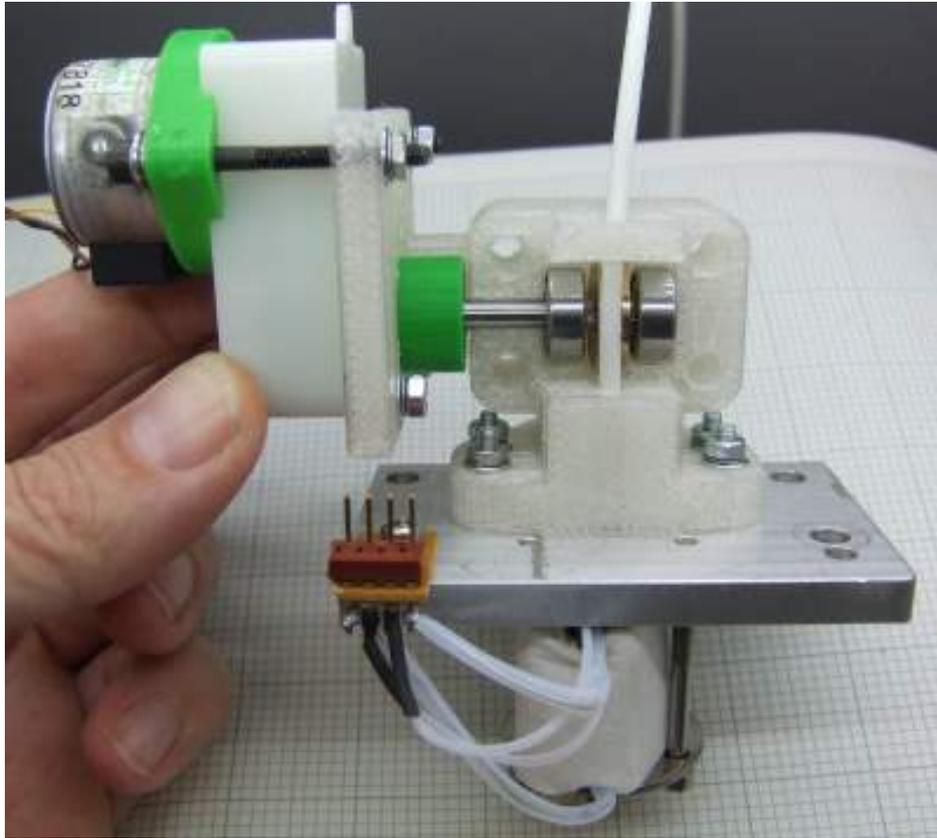
# Fast extruder

Wednesday, 26th August 2009 by Nophead

I put together my new extruder controller, the worm pulley drive mechanism with the GM17 tiny stepper hack and the stainless steel extruder with heatsink and ducted fan to make possibly the most complicated extruder design yet!



You can see a better view of the drive mechanism fitted on another extruder base here: -



Here is a reminder of what the heater assembly looks like: -



The heatsink is cooled by a tiny fan. When run from 12V it is very noisy and way too powerful. With my new controller I can run it with PWM just a bit faster than its stall speed. That keeps the noise down and still gives more cooling than needed. I attached a thermistor to the heatsink by gluing it into a crimp tag with J-B Weld.



I can tell the controller to keep the temperature below a specified level by turning the fan on and off. I set the trip point to an arbitrary 35°C. It will even turn it on when the extruder is idle, much like the radiator fan of a car runs after the engine is switched off. This is needed to ensure PLA will never soften and jam in the cold part of the tube.

I run the tiny stepper motor at about 300mA to keep it cool enough to touch. It will take more current than that but runs very hot. A good design would use a single fan to cool the motor and the heatsink.

I ran the motor with micro stepping, so even though it has a 15° step, that gives 192 steps per revolution. The GM17 gearbox has a reduction of 228:1 giving a massive 43,776 steps per revolution of the worm pulley. That seems a lot, but the diameter of the pulley is 13mm, so one turn is 40.84mm of feed. That gives 1072 steps per millimetre. In comparison I have been using an 816 step shaft encoder and an 0.8mm pitch thread, which gives 1020 steps per millimetre, almost the same.

I started extruding ABS with my usual feed rate of 16mm/s for 0.5mm filament, which is 3.14 mm<sup>3</sup> per second. I kept doubling it until it failed, which was 128mm/s if I have got the calculations right. At that point it mostly worked but something was slipping occasionally. I think it was the clutch in the gearbox. Backing off to 64mm/s it works fine. That is four times faster than the GM3 manages with a screw drive. It is too fast for HydraRaptor but I reckon my Darwin could go that fast. I have no idea what the build quality would be like but it would get the time to print one down to about 24 hours.

Here is a video of it spewing out plastic.

[Fast Extruder from Nop Head on Vimeo.](#)

It isn't mechanically compatible with HydraRaptor without making a new bracket to mount it on the

z-trolley, so I haven't made anything with it yet.

# Pear shaped

Tuesday, 1st September 2009 by Nophead

My wife has a tiny orchard in our front garden, four fruit trees on dwarf stock. This year the espaliered pear tree has got a bit out of hand and has produced pears that are too high for us to reach and too far away to reach from a step ladder. In fact some are actually outside of our garden! The tree should really be 2D but it has gone a bit 3D on us.

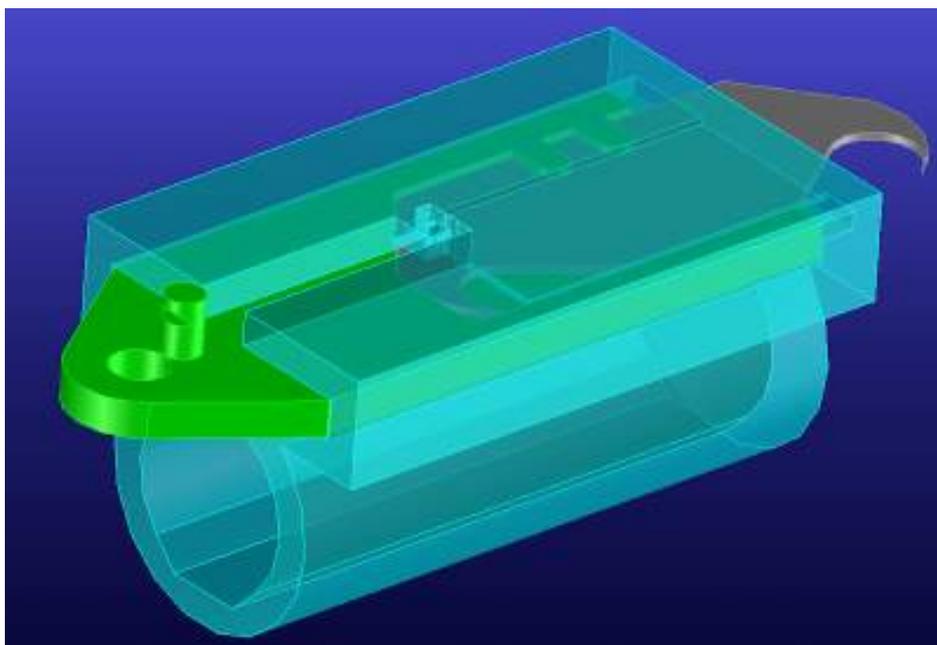
So RepRap to the rescue, I made a device to cut pears at a distance and another device to catch them.

The cutter is based on a hook shaped Stanley knife blade No 1996. I made a sliding carrier for it with a hole to attach a string and a peg to take a spring.



This fits inside a casing with a tube to mount it on the end of a 16mm OD pipe. A spring keeps the blade extended. A string is pulled to retract it to cut the stem of the pear.

This drawing shows how the parts fit together inside.



There is a rib in the top that prevents the blade from lifting over its locating bumps. The casing was made upside down and makes heavy use of bridge spanning to avoid the need for support material.

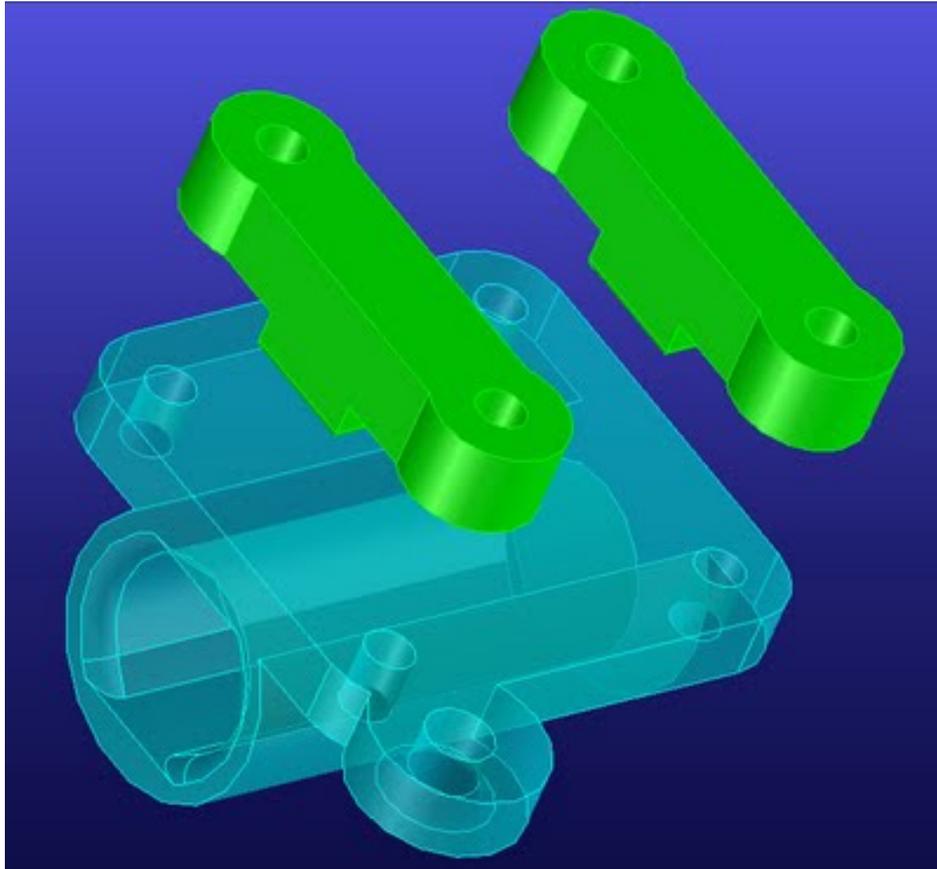


As a mechanism it worked well, but useless for cutting pears as I completely underestimated how tough a pear stalk is. So onto plan B, a pair of secateurs clamped to a pole, with a piece of string threaded through an eye to pull them closed: -



The handle of the secateurs is a horrible shape for making something to mate with it because its

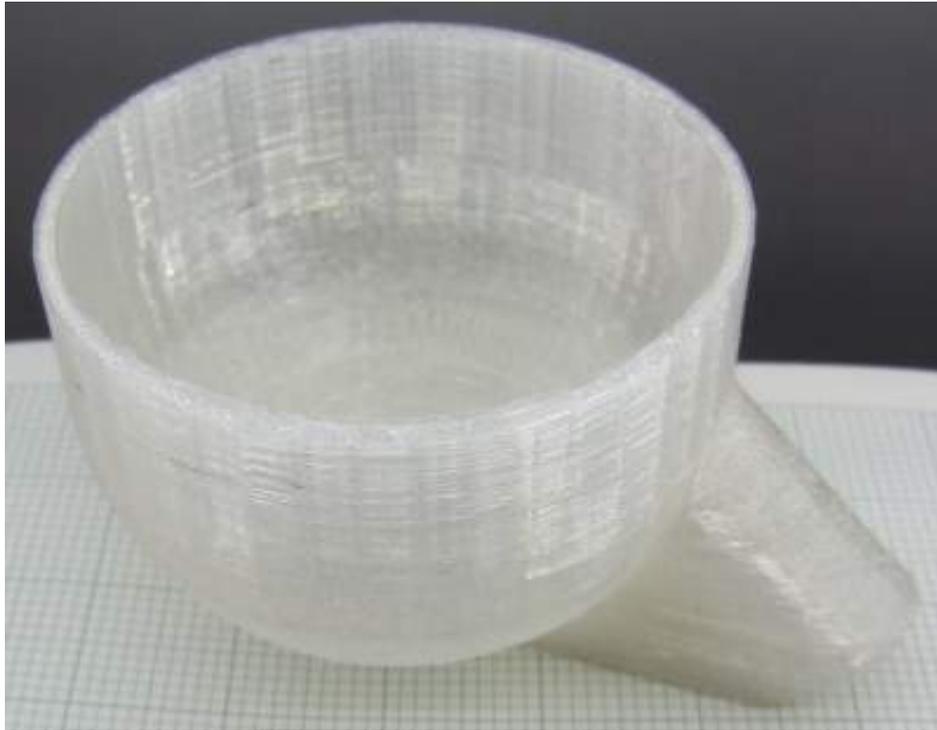
surfaces are irregular curves (not arcs or ellipses) in two dimensions. Very difficult to model without a 3D scanner. I made use of a channel in the back to be able to grab it with simple flat parts.



This version works well, with a handle to make the other end of the string easy to pull: -



A cup mounted on a second tubular pole catches the pear.



It is a two person job to use both at the same time. A better design would be to mount both tools on the same pole somehow. A better catcher could be made by a plastic bag sandwiched between two circular hoops of plastic to hold the top open.

Here it is in use: -



The only design issue is that it is hard to see where the jaws of the secateurs are when looking along the length of the pole. Mounting the pole at an angle to the clamp would solve that.

Here are the extra out of reach pears that we cropped with the contraption.



The files are available on [Thingiverse](#).

# Hairy Pea

Tuesday, 29th September 2009 by Nophead

I have had a few anonymous requests for a new post, so here is an object I made recently: -



It is a whistle downloaded from [Thingiverse](#) designed by [Zaggo](#). It must be one of the most printed things on Thingiverse, and in a very short time after its posting. I think the reason it is so popular is that it is a functional item with a moving part (the pea) that is printed in situ. It is attached by one small point at its base and you detach it by pushing a scalpel through the slot.

It is very loud and annoys my wife every time I blow it!

The pea was initially very hairy because I get a lot of ooze with PLA. I had to pick the hairs off it through the slot, a bit tricky. I am currently working on a new extruder (when am I ever not?) with a much shorter melt zone to address this.

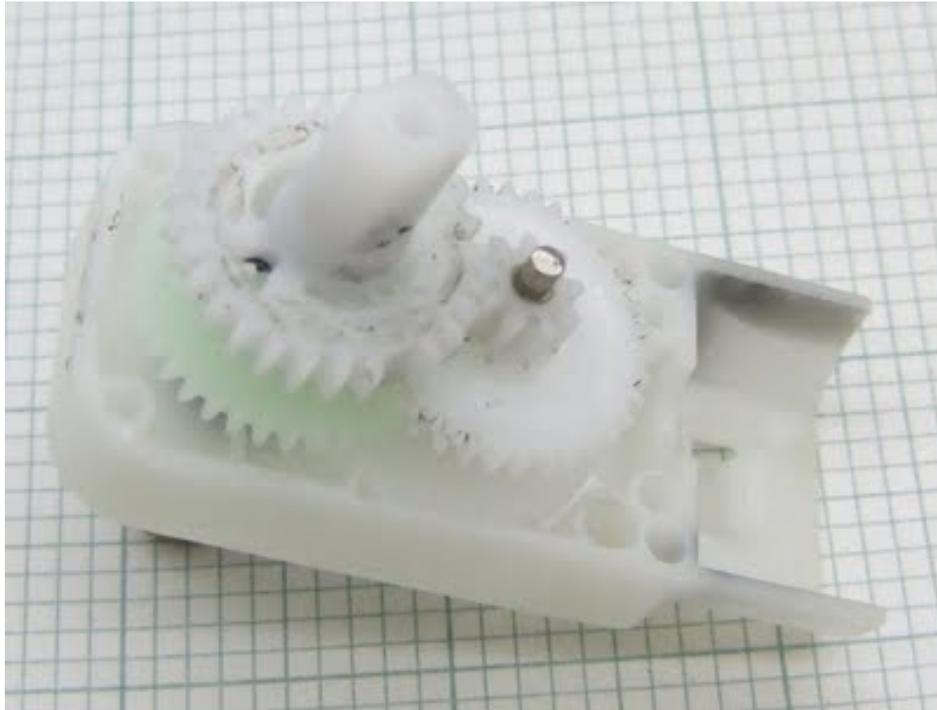
The reason I haven't posted for so long, apart from being on holiday in the [Spanish Pyrenees](#), is that I have spent a long time thinking about the design of this one. It will also be super sturdy, so hopefully it will allow me to forget about extruders and move on to other things. I.e. new heads for HydraRaptor as it has spent too long having only two, so not living up to its name.

# Toothless

Saturday, 17th October 2009 by Nophead

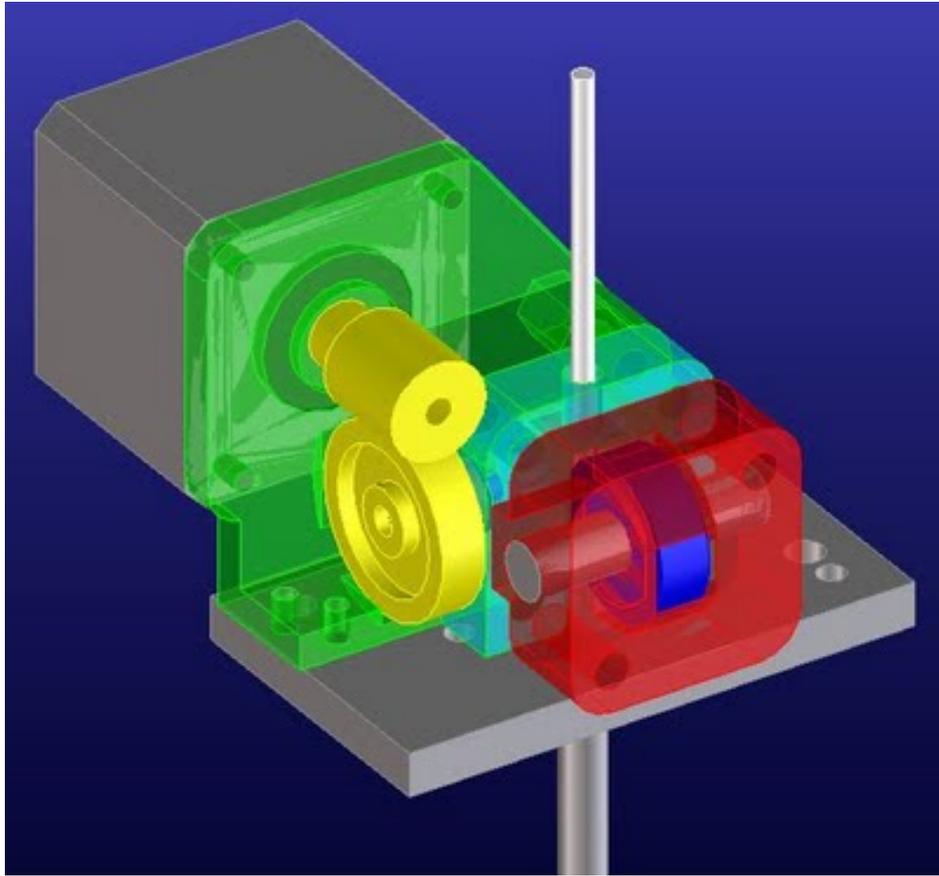
Irritatingly, whenever I try to make a new extruder using my existing one, it always breaks down forcing me to have to repair it, even though it is about to be made obsolete. It is as if they know!

The GM3 motor on my extruder started making a noise like a machine gun. On opening it up I found it has stripped a tooth of the final gear.



Since I moved from the 6V version to the 12V version I have been getting pretty good motor life. I do have to lock the clutch and sometimes glue the splined shaft into the last gear, but so far the gearbox has lasted well.

It is just as well my next extruder uses a stepper motor and an all metal drive chain: -



More details soon ...

# Worm drive

Sunday, 25th October 2009 by Nophead

I have spent a long time trying to make an extruder that is reliable, performs well and is cheap and easy to make. My last design fits most of those criteria but I have doubts about how long it will last because I am putting a lot of torque through the plastic gears of the GM17 gearbox. These doubts were heightened when a tooth snapped in a GM3 gearbox that I have been using for a long time.

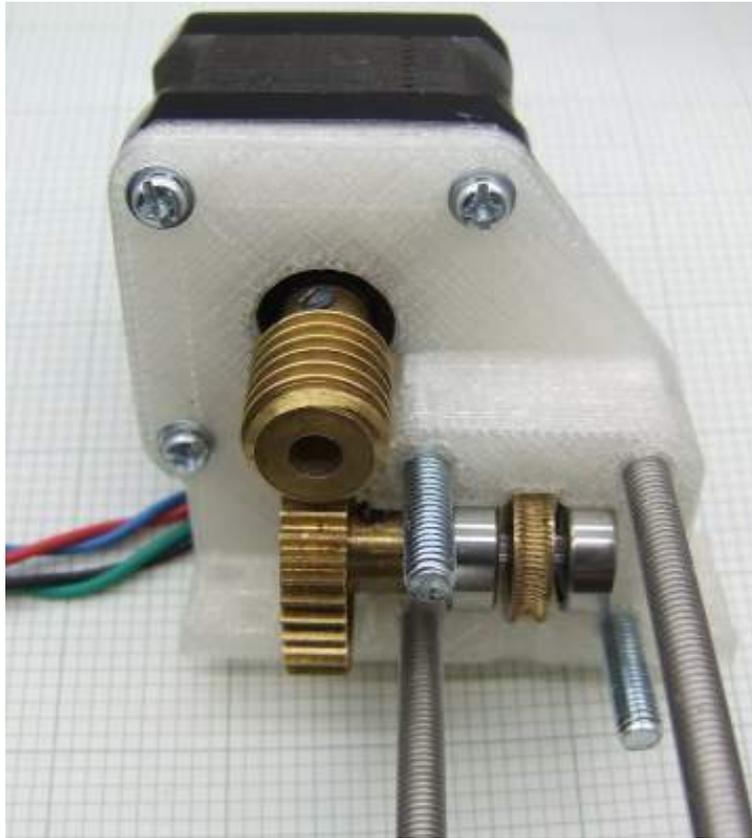
I decided to make a new extruder for HydraRaptor concentrating on performance and reliability. I have tried to pull together all the results of my experiments to pick the best solution for each part of the design, regardless of cost and ease of building. The result is a "no compromise" design that has taken me a long time to make. Hopefully it will be reliable so that I can move on to exploring other things.

The design criteria for an extruder for HydraRaptor are a bit different from Darwin. The weight of the extruder is far less important because it is a moving table machine (rather than moving head). The z-axis is a big slab of aluminium so I don't need a heatsink or fan, I can just conduct the heat away.

I found that the best form of traction is a "worm pulley". Screw drive has slightly more grip on softer plastic but is far less mechanically efficient. It also has the nasty habit of making the feedstock rotate in some cases and also generates dust.

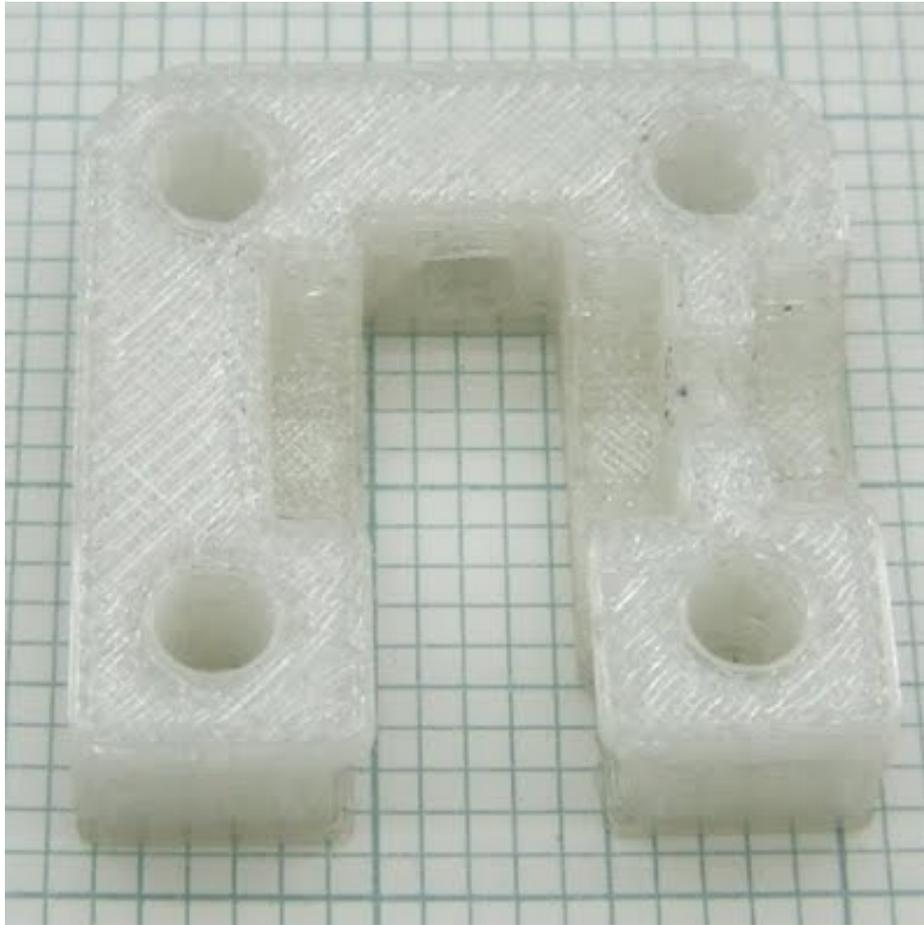
The pulley can impart in excess of 100N force on the filament before it slips, so to have the grip as the limiting factor we need a motor that can provide that amount of torque. The pulley has a radius of 6.5mm so that equates to 0.65Nm. I could do that with direct drive off a NEMA23, but even with micro stepping a single step is quite a lot of filament:  $13\text{mm} \cdot \pi / (200 \cdot 8) = 0.025\text{mm}$ . That doesn't seem much but 0.5mm filament comes out 36 times faster than its 3mm feedstock goes in, so that is almost 1mm extruded per step. That seems way too big for accurate control to me, so some gearing is necessary.

A worm gear is attractive because it gives a big reduction in one step so I came up with this arrangement: -

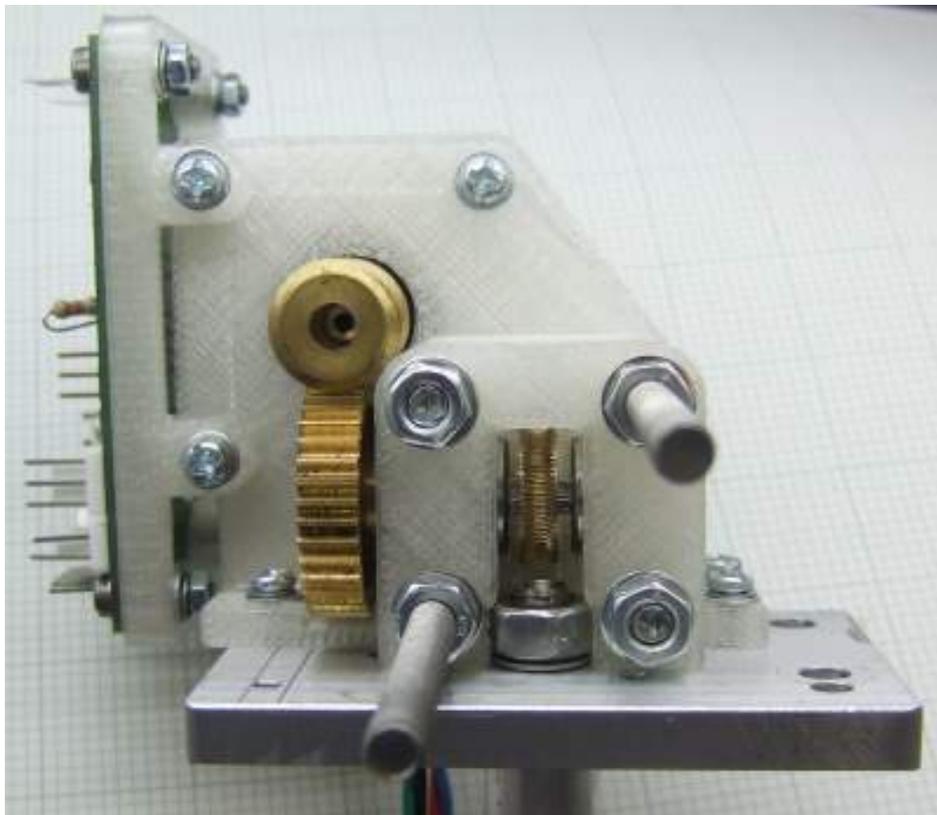


The pulley is on a 4mm splined shaft supported by two ball bearings. The gears are Meccano gears which are readily available. I couldn't find any other metal gears at reasonable prices. I had to drill out the worm wheel to fit the motor shaft. I filed flats on both shafts to allow the grub screws to grip.

This bearing cover holds the bearings in place and guides the filament: -

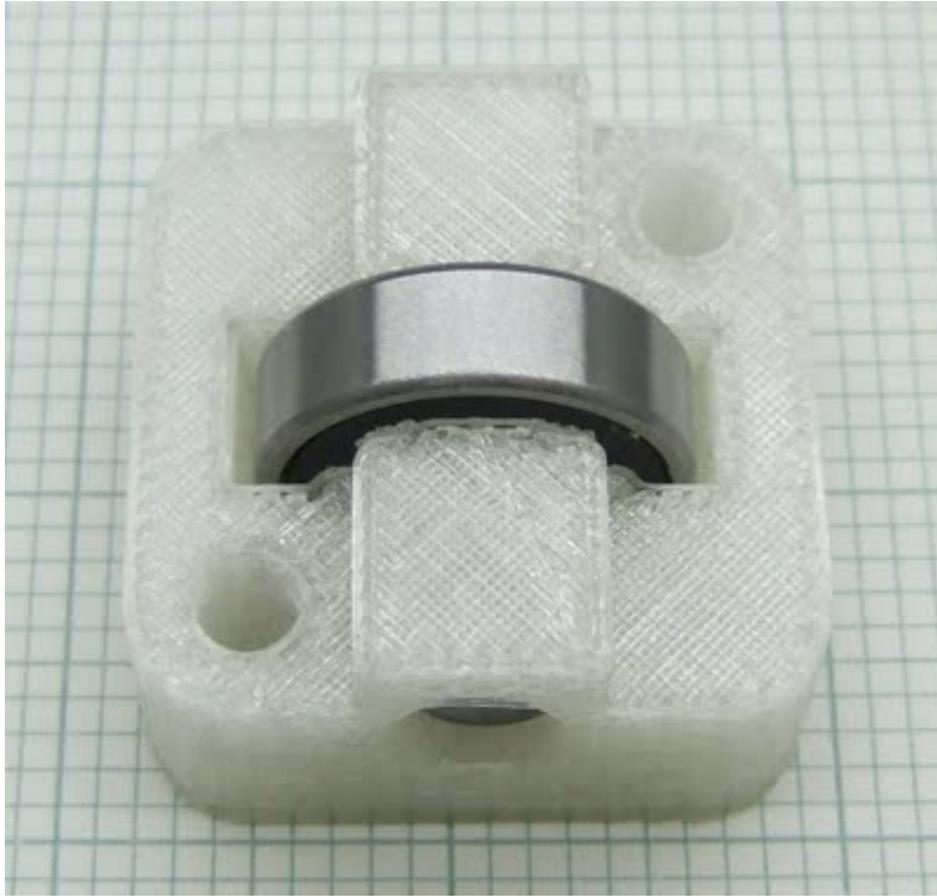


The assembly is clamped together by M5 hex head bolts that are captive in the plastic.



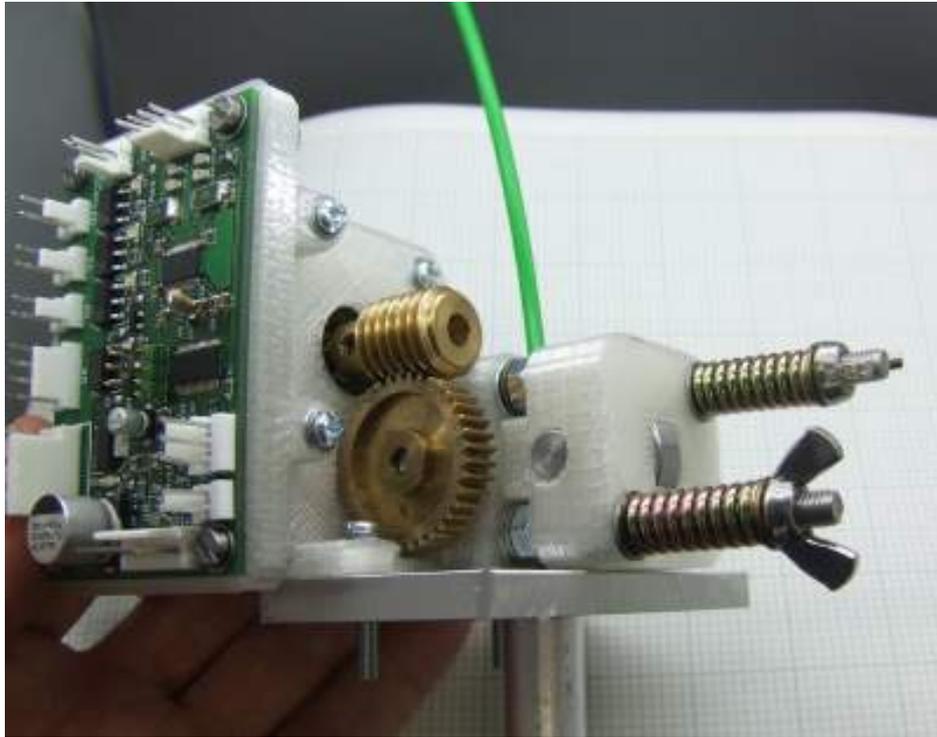
You can see the top of the stainless steel pipe that the filament feeds into. It has an aluminium outer sleeve to conduct the heat away from the transition section, rather than a heatsink. More on that later.

A skate bearing is used as a roller to apply pressure to the filament: -



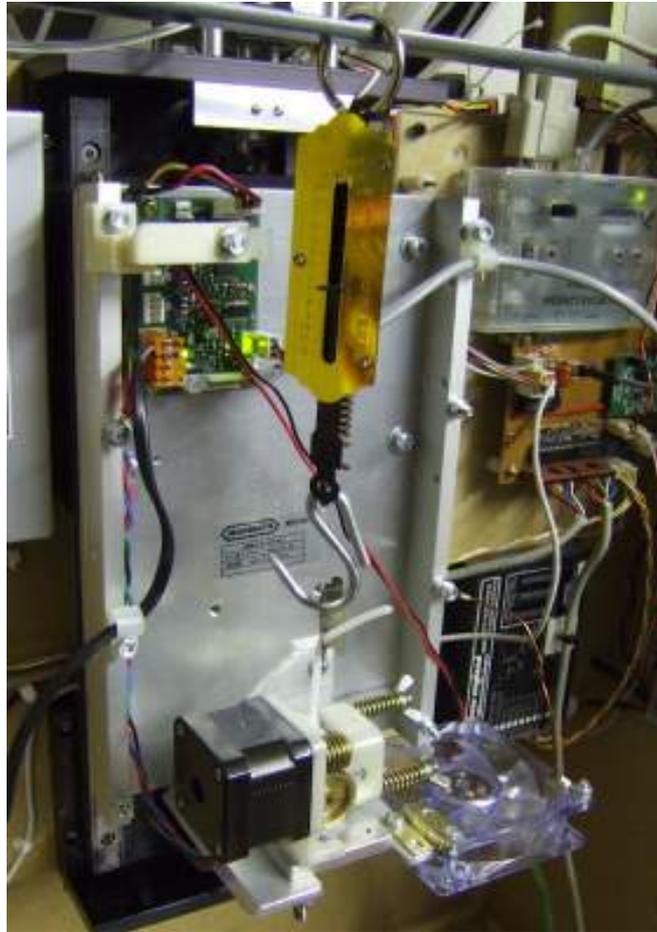
A piece of M8 studding forms the axle. It is held in place just by friction. The bearing is centralised by cheeks on the plastic which are clear of the moving part.

The pressure is applied by springs and M5 wingnuts: -



The nuts on the bearing cover prevent the roller from meeting the drive pulley when there is no filament. That allows filament to self feed easily simply by inserting it into the hole in the top.

I measured the performance by attaching a spring balance to the filament and measuring the force at which the motor stalled for a given current: -



The motor is a NEMA17 rated at 0.3Nm holding torque with two coils on at 2.5A. The reduction ratio is 40:1, so I expected to only need about  $0.637 / 40$  to give a 100Nm pull. I was disappointed to find that I needed 1.5A to pull 10Kg.

With sinusoidal micro stepping drive the holding torque will be 0.7 times the two coil on value. I.e. 0.21Nm @ 2.5A, so 0.126Nm @ 1.5A. The torque from the pulley is only 0.016Nm assuming a reduction of 40:1, so the worm drive is only about 13% efficient if I have got my calculations right. Before I greased it, it was only half as efficient, so worm gears certainly waste a lot of effort in friction. The article [here](#) says they are between 98% and 20% for ratios 5:1 to 75:1, so I am probably in the right ball park. There will also be some friction in the bearings and pull out torque will be a bit less than holding torque, even though it is only rotating slowly.

So it reaches the target torque but with far less efficiency than my version with the tiny motor and the GM17 gearbox.

The other disappointment is that it is quite noisy, even when micro-stepping. That is simply because the z-axis couples any vibration to the wooden box behind it that then amplifies it. I am tempted to fill it with something to dampen it down.

So this half of the extruder seems to perform, and it should be reliable because there is not much to wear out, except perhaps the worm gears, that is where most of the friction is and they are only made of brass.

I will test the bottom half of the design tomorrow.

# Hacking with Erik

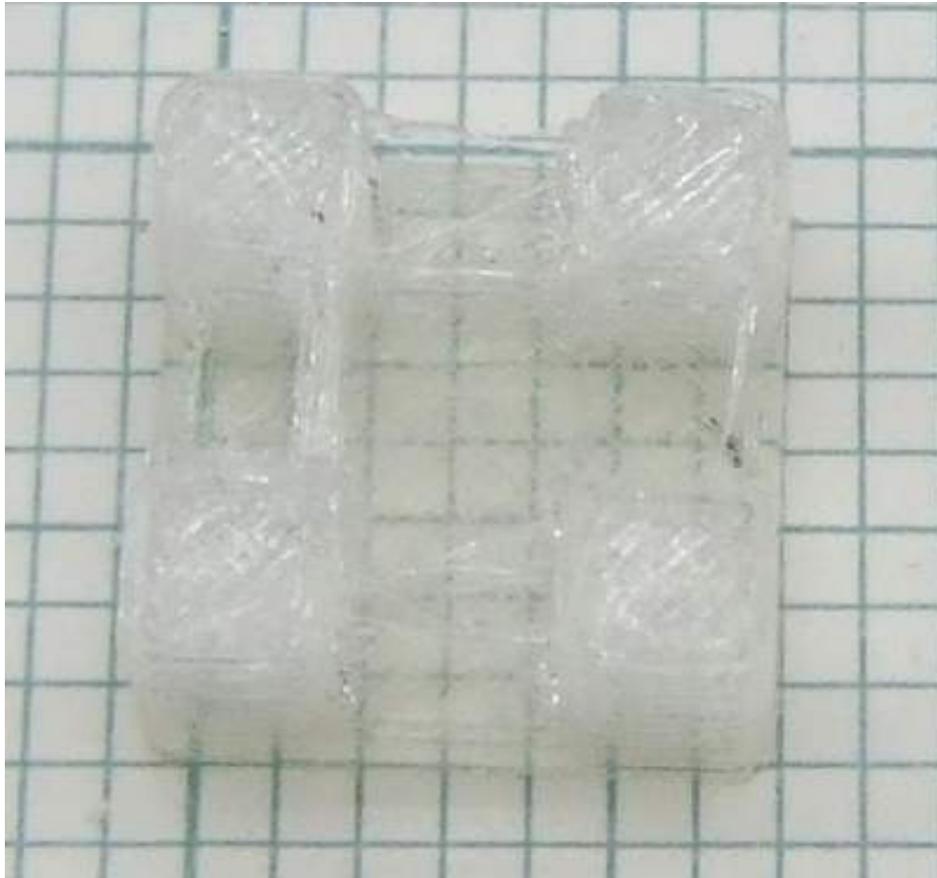
Tuesday, 3rd November 2009 by Nophead

Erik de Bruijn (RepRap evangelist) is in the UK at the moment visiting Salford and Nottingham universities to spread the word. Yesterday he came here to see HydraRaptor. We spent a very interesting afternoon and evening, swapping extruder ideas, comparing objects we had made, and doing a couple of very successful experiments.

The first was something I had been wanting to try for a long time, and that was reversing the extruder drive to stop ooze. My latest extruder (details to follow) has a much smaller melt chamber but still has significant ooze when extruding PLA. Erik is pursuing the Bowden extruder idea, which should benefit even more from reversing.

Because my machine is controlled by Python, rather than g-code, it is very easy to try out things like this. We hacked the code to instantaneously reverse for a short distance very quickly at the end of each filament run. After moving to the start of the next run it fast forwards the same distance that it reversed before resuming the normal flow rate.

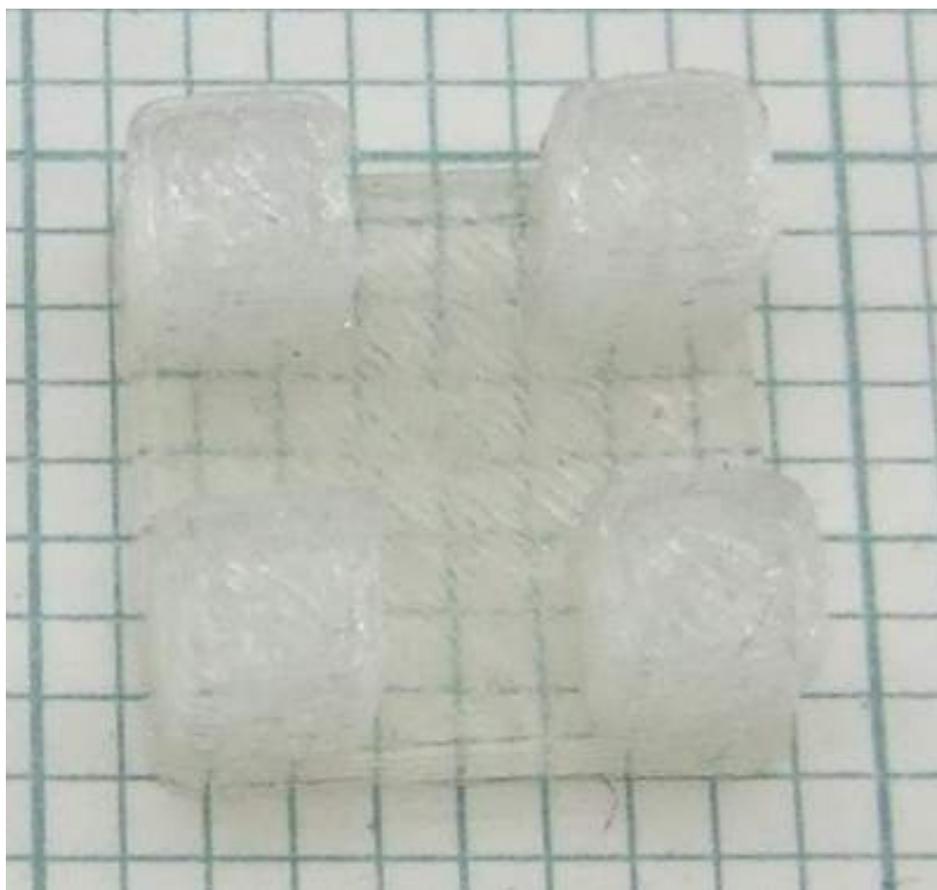
I designed a simple test shape to allow the results to be compared. It is a 15mm square with four 5mm towers at each corner. I am not using Enrique's latest Skeinforge which I think would minimise the extruder moves in fresh air to just three per layer. This is with a very old version that does the four outlines and then returns to fill each of them in.



Plenty of hairy bits showing the ooze. These can be removed easily, but what is worse is the object will be missing that amount of plastic making it weaker. This can be extreme with a thin structure which is remote from other parts of the same object.

We tried reversing 1 mm at 8 times the extrusion speed to start with. That worked but was obviously more than was needed. We tried 0.25mm which was too little and settled on 0.5mm, although a lot of that is taken up by the motor bracket flexing. I need to make it stronger.

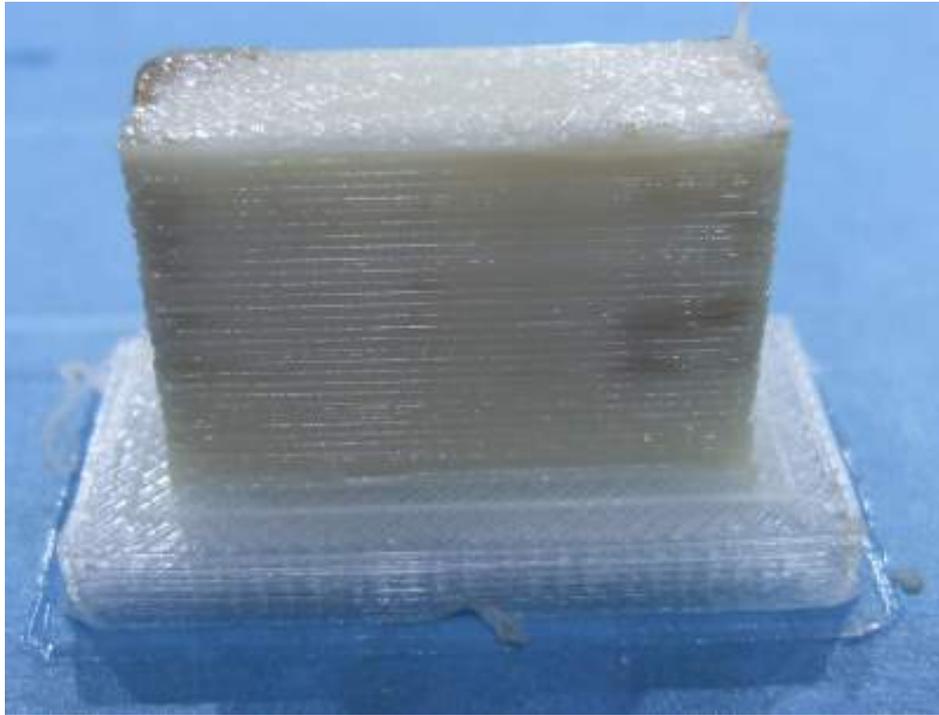
The result was no hair at all!



A very simple fix for a problem that has used a lot of my time in the last two years.

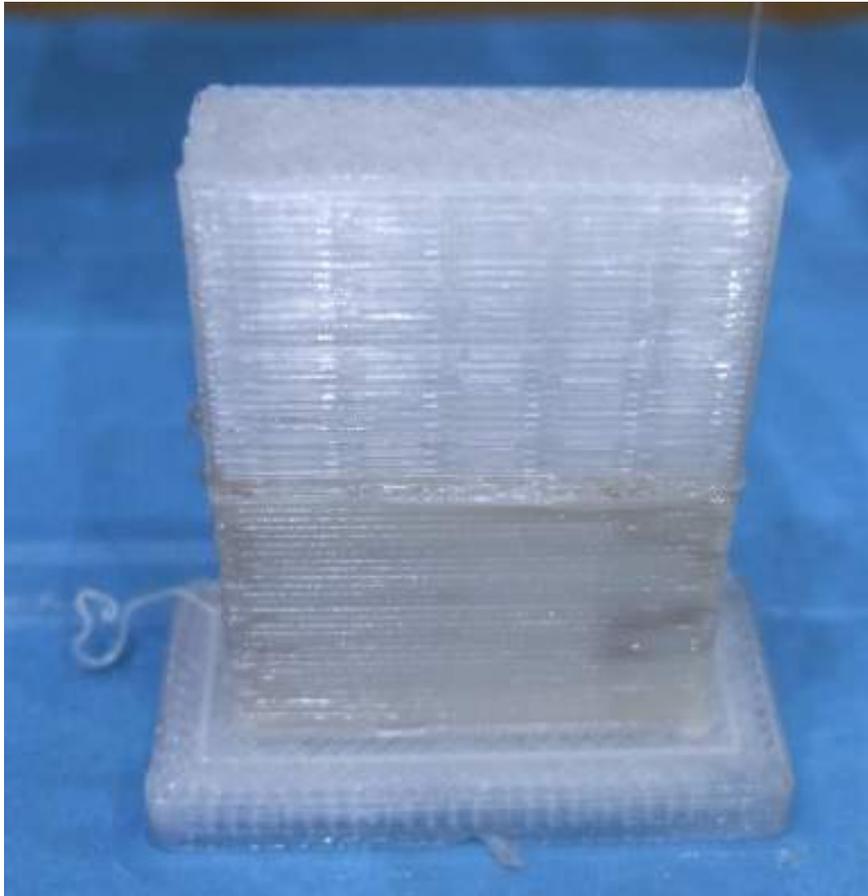
The second experiment was something Erik wanted to try. He has discovered that PLA is soluble in caustic soda, so potentially could be used as soluble support material for ABS. The question was: can we extrude ABS onto PLA and get it to stick well enough to resist warping?

We made a 5mm thick slab of PLA 20mm wide and 40mm long, 90% fill. On top of that we extruded a 30 x 10 x 20mm block of ABS with a 25% fill.



The ABS looks very glossy so I think it may have some PLA in it. Possibly we needed to flush it through for longer. The ABS block is also a bit scrappy. The reason was that the extruder was playing up. It was leaking plastic, hence the burnt bits and the stepper motor was skipping steps leaving a deficit of plastic. This extruder had never done ABS before and still has some teething problems, but it shows that ABS will bond to PLA well enough to stop it curling.

Next we extruded a block of PLA on top of the ABS.



That also bonded well. The messy bit at the join is because HydraRaptor did its normal circuit of the object that it normally does on the first layer but it was in mid air.

To see how well they were bonded we put the PLA base in a vice and attached a small g-clamp to the PLA block on top. The g-clamp was pulled with a strain gauge until the ABS came way from the base at about 8Kg. Interestingly the first layer outline of the ABS was left on the PLA. That was deposited at 215°C whereas the infill of the first layer was at 195°C. These are the values I use for depositing ABS onto a raft, so in an object layer on top of support it would be 240°C giving a stronger bond. See Erik's writeup and video [here](#).

So PLA looks like a good candidate for supporting ABS. They bond well and PLA is very rigid to resist warping. It can be dissolved with drain cleaner but also I expect it would be easy to peel when softened in hot water.

All in all a good day's hacking.

# No compromise extruder

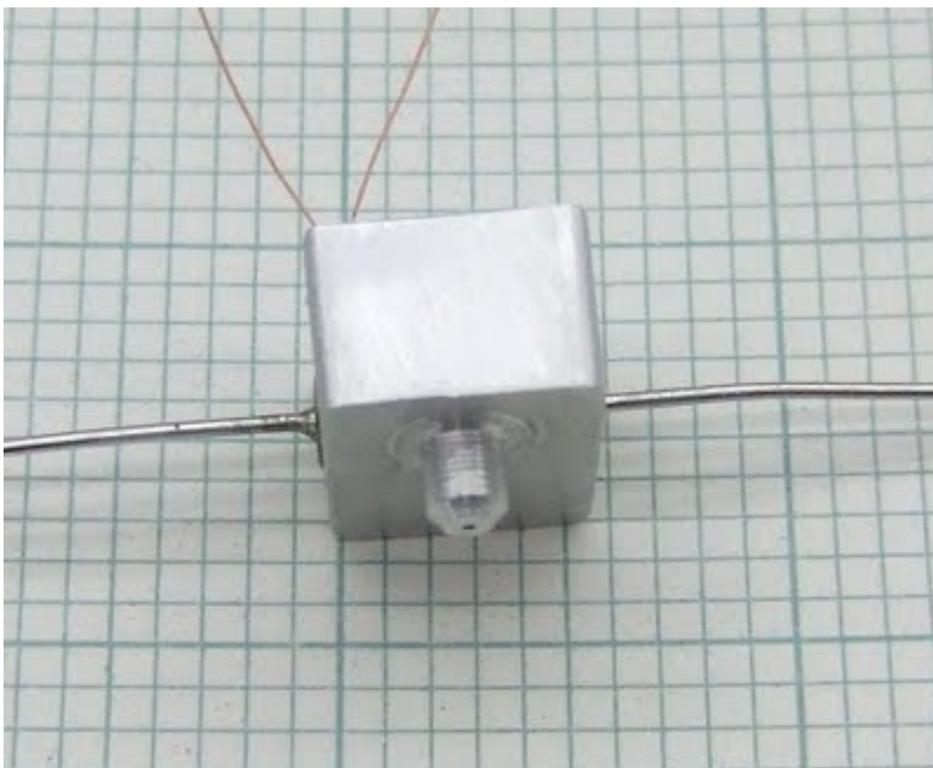
Wednesday, 4th November 2009 by Nophead

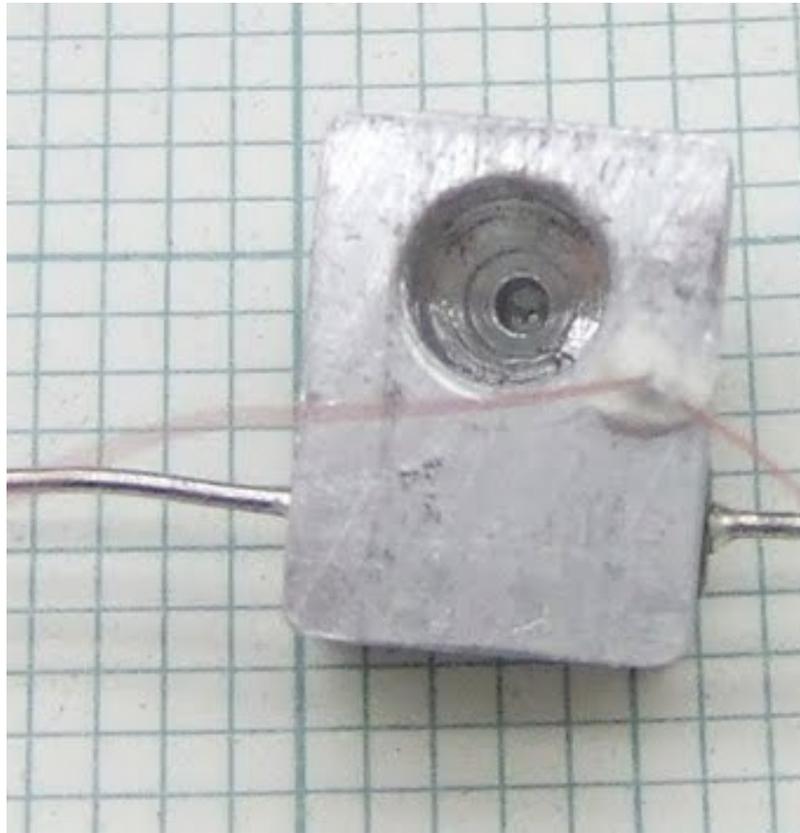
I have settled on using vitreous enamel resistors embedded in an aluminium block for the heater. I think they are the easiest heater to make and likely to be the most durable. They also work fine with simple bang-bang control, whereas it would appear that the Nichrome and Kapton version requires PID.

One of the aims of my new design is to reduce the amount of molten plastic to minimise ooze. Also less molten plastic means less viscous drag. I also wanted to reduce the thermal mass (to reduce the warm up time) and completely cover the hot part with insulation to allow a fan to blow on the work-piece without cooling the nozzle.

To achieve these aims I switched to a smaller resistor (same resistance but less wattage) and mounted it horizontally rather than vertically. There is some risk that the resistor may fail but I think as long as it has good thermal contact with the aluminium block, so that its outside temperature is less than 240C, then I have a good chance it will last.

The smaller resistor also means a much smaller surface area so less heat is lost. To keep the molten filament path as short as possible I combined the heater and the nozzle and made it from one piece of aluminium. That also gives very good thermal coupling between the nozzle tip, the melt chamber, the heater and the thermistor.

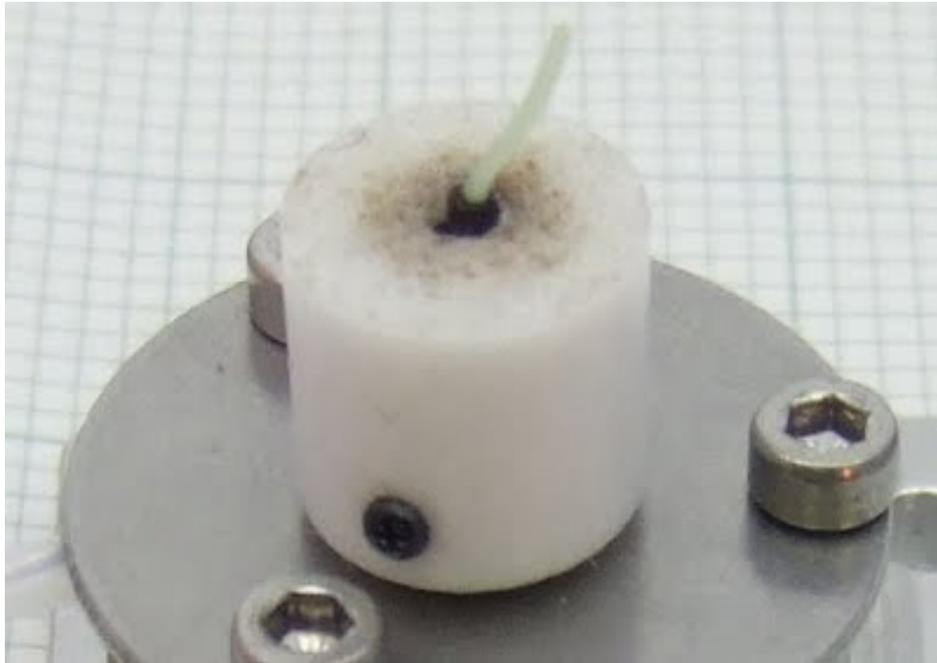




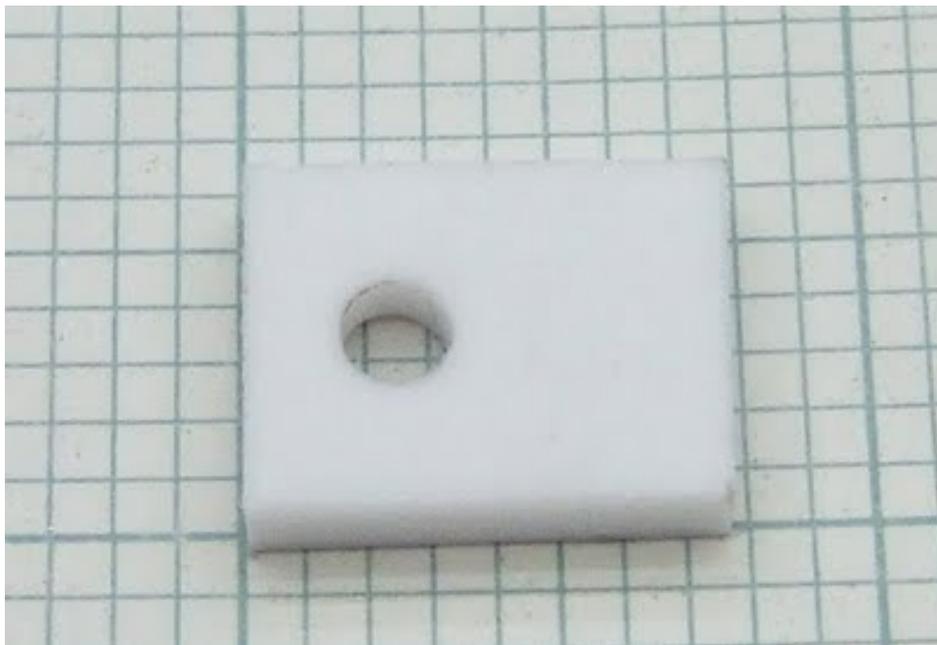
I turned it out of a block of aluminium using my manual lathe and a four jaw chuck, but I think I could also mill it out of 12mm bar using HydraRaptor.

A feature that I have used on my previous extruders is to cover as much of the nozzle as possible with PTFE. That stops the filament sticking so that it can be wiped off reliably with a brush. It also insulates the nozzle.

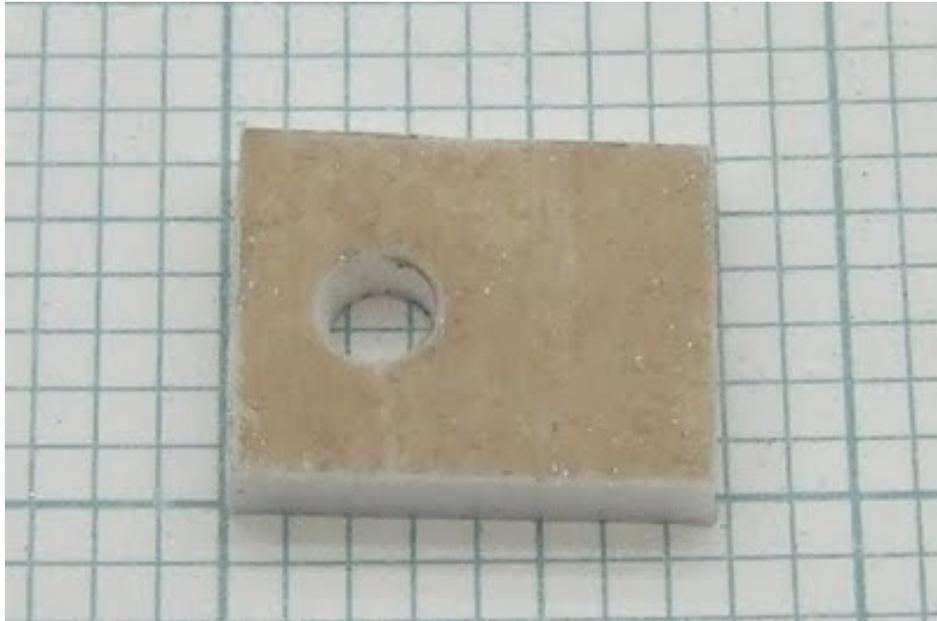
My previous nozzle cap implementations have been turned from PTFE rod. The downside of that is that the working face, that has been cut and faced on the lathe, is not as smooth and slippery as the original stock.



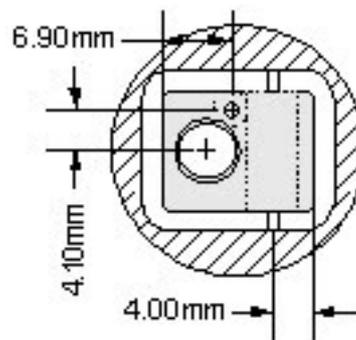
To cover the face of this version I used a 3mm sheet of PTFE so it has the original shiny surface.



Normally PTFE is too slippery to glue so my original plan was to screw it on with some tiny countersunk screws. However, the sheet I bought was etched on the back to allow it to be glued, so I stuck it on with RTV silicone adhesive sold for gluing hinges onto glass oven doors.



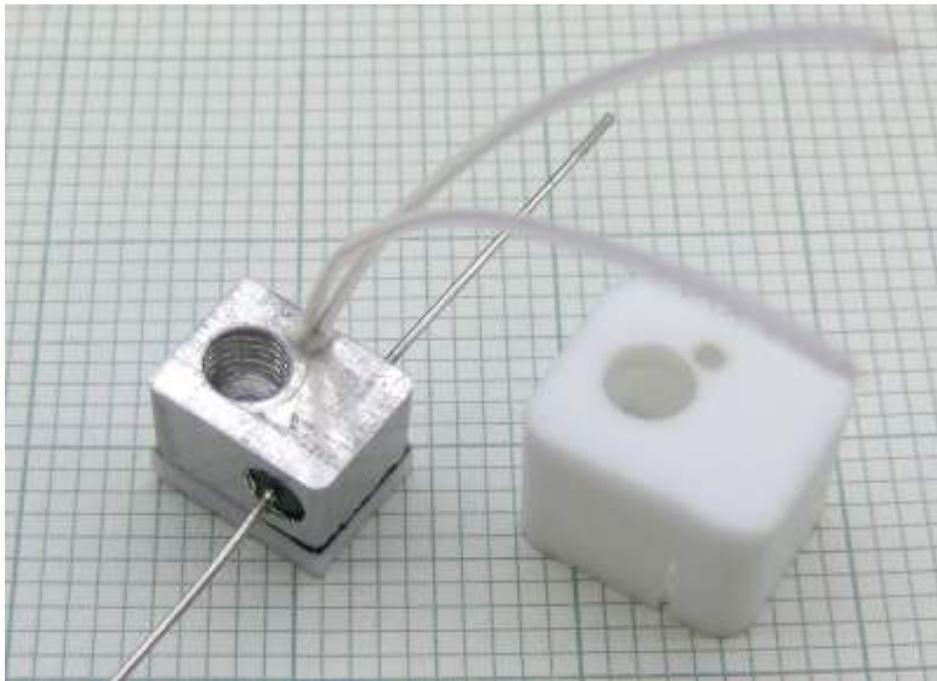
To insulate the rest of the heater I milled a cover out of a slice of 25mm PTFE rod.



I normally stick items to be milled onto the back of a floor laminate off-cut using stencil mount spray. I didn't think that was going to work with a PTFE cylindrical slice that is only a little bigger than the finished item. Instead I milled a hole in a piece of 6mm acrylic sheet that was already stuck down with stencil mount. The hole was slightly smaller than the PTFE so I faced it and chamfered it on the lathe and then hammered it in.



I roughed the shape with a 1/8" end mill and then sharpened the internal corners and cut the slots for the resistor leads with a 1mm end mill. I tried to mill the whole thing with a 1mm bit but it snapped due to a build up of burr in the deep pocket. On reflection it was silly to expect to be able to mill deep pockets with a 1mm bit and of course it is much faster to rough it with a bigger bit.



I used my normal technique of taking 0.1mm depth cuts at 16mm. That allows me to mill plastic with no coolant, but I expect I could have made much deeper cuts in PTFE. It mills very nicely, probably because it is soft and has a high melting point and low friction.

I haven't done any milling for a long time so for anybody new to my blog here is my the milling set-up: -



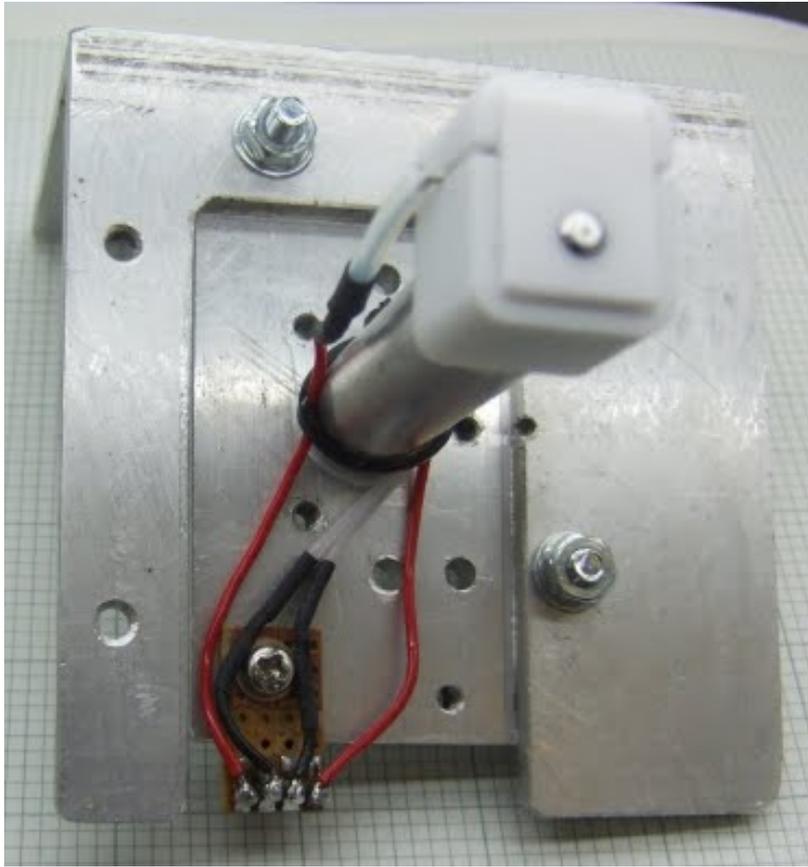
It is simply a Minicraft drill with some very sturdy mounts. The spindle controller I made originally would need its micro replaced as the one I used has a bug in its I<sup>2</sup>C interface. Instead I just connected it to the spare high current output on my new extruder controller.

The remaining part of the extruder is the stainless steel insulator.

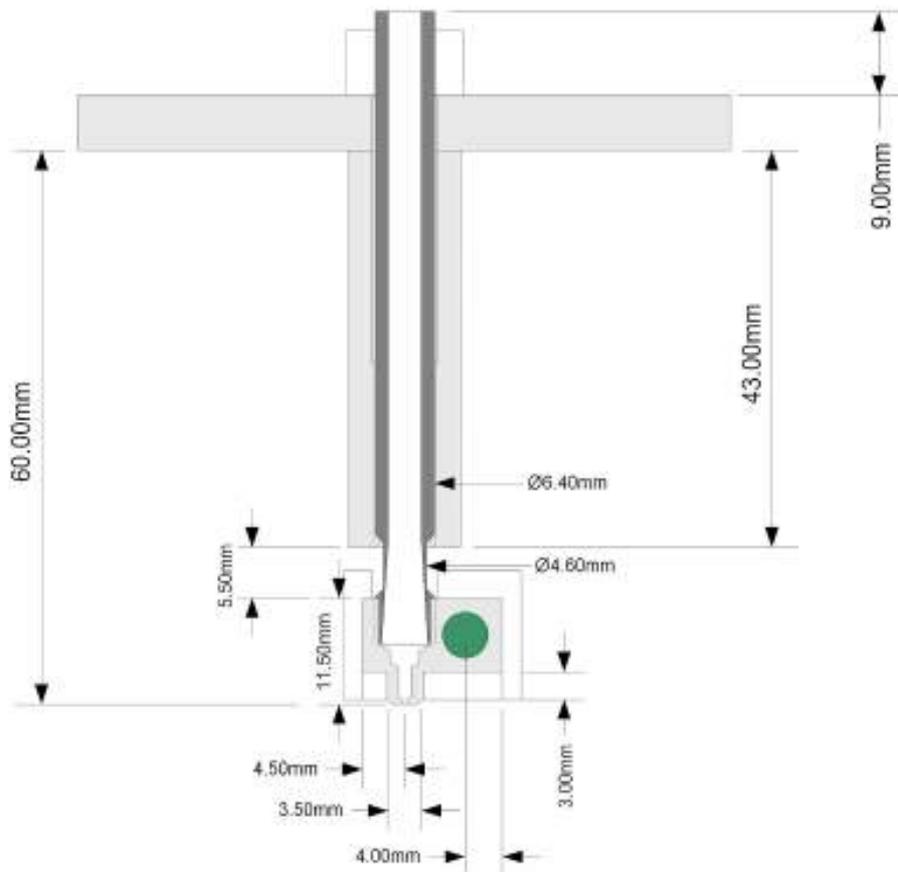


I made the transition zone shorter than the last one I made because I wanted all of the inside of the transition to be tapered. The aluminium sleeve carries away the heat from the cold end of the transition to an aluminium plate that forms the base of the extruder. That in turn carries the heat to the z-axis via an aluminium bracket. I used heatsink compound on the joints.

Here is a view of the bottom half of the extruder: -



And here is a cross section showing the internal details: -



So that was the plan, what could go wrong? Well everything really! The first problem was that the resistor shorted out to the aluminium block. The smaller resistor only has a thin layer of enamel over its wire. Normally I wrap aluminium foil round it to make it a tight fit. I didn't drill the hole big enough so it was a tight fit with only one layer and pushing it in abraded the enamel. The solution would be a bigger hole and more layers of foil, but I just glued it with Cerastil as a quick fix. Of course it only failed after I had fully assembled it and run some heat cycles so I had to strip it down again to fix it. Not easy once the wiring has been added.

The next problem is that it leaks. I think it is because I dropped the extruder when I was building it and bent the thin edge at the end of the stainless steel barrel. That forms the seal with the heater block, so even though I straightened it I think the seal is compromised. I keep tightening it and thinking it is fixed but after hours of operation plastic starts to appear at the bottom of the PTFE cover.

The other problem is that mostly it extrudes very well, I now do the outline at 16mm/s and the infill at 32mm/s, but sometimes the force needed to push the filament gets higher and causes the motor to skip steps, or the bracket to bend so far that the worm gear skips a tooth.

I have made several objects taking between one and two hours and it worked fine. Other times, mainly when I was making small test objects with Erik, it will completely jam. Actually it seems to jam when it is leaking badly, which implies the pressure of the molten plastic is much higher as well as the force to push the filament. The only explanation I can think of is there is an intermittent blockage of the nozzle exit. More investigation required.

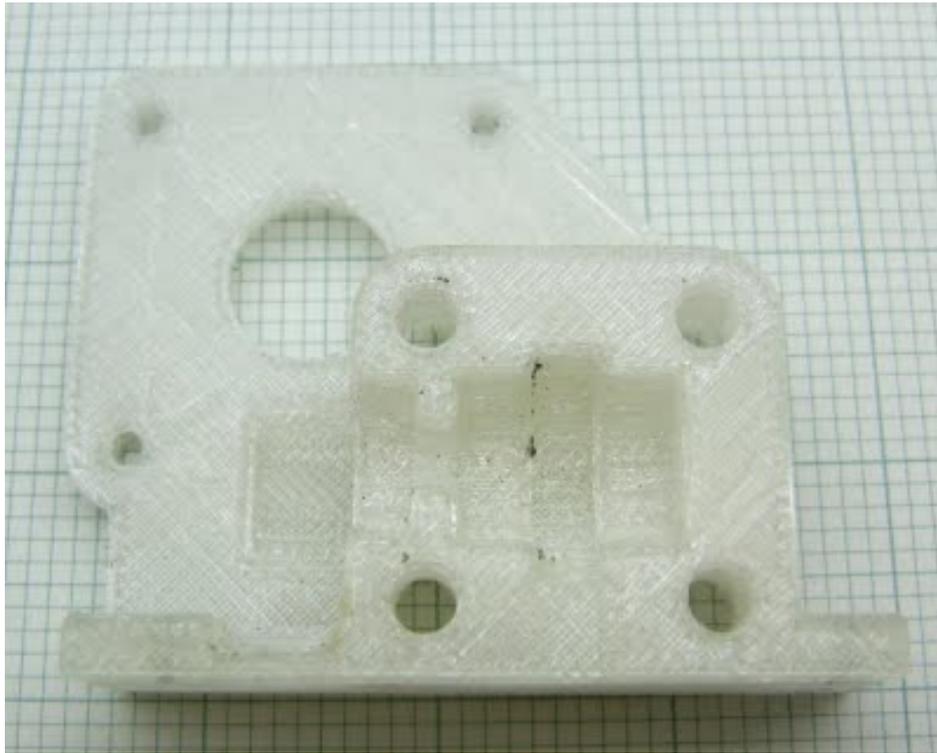
# Beefed up bracket

Friday, 20th November 2009 by Nophead

When I started reversing my extruder I noticed the motor bracket flexing. Here is a short video showing it in operation: -

[BendyExtruder](#) from [Nop Head](#) on [Vimeo](#).

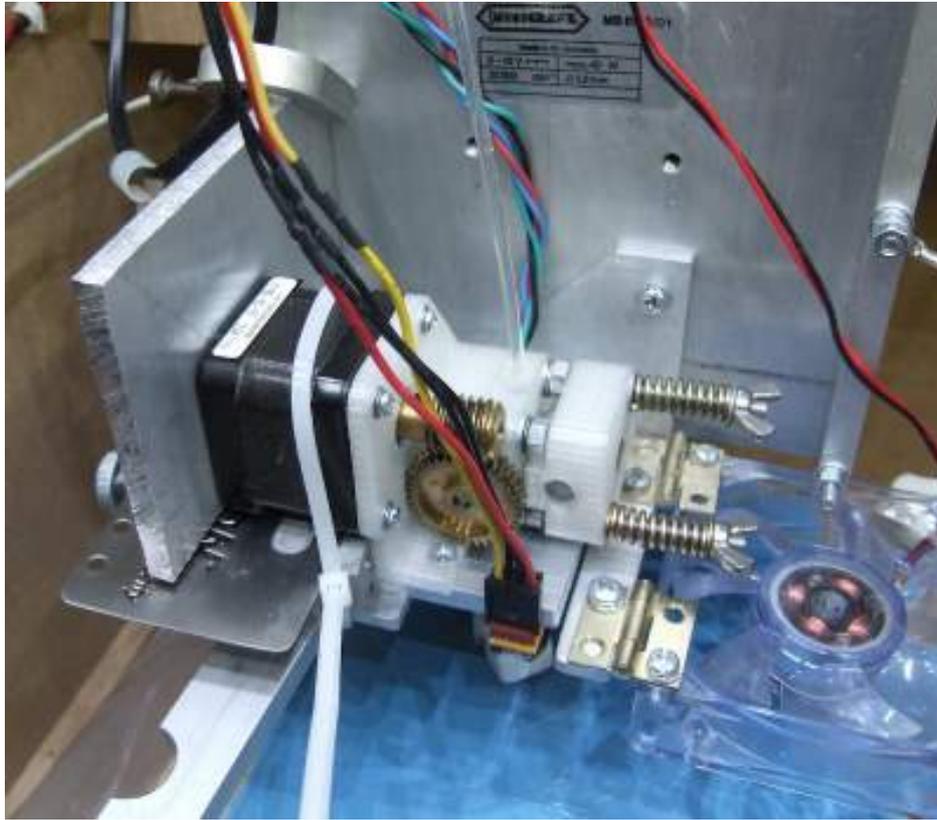
It was immediately apparent that I had not made it strong enough.



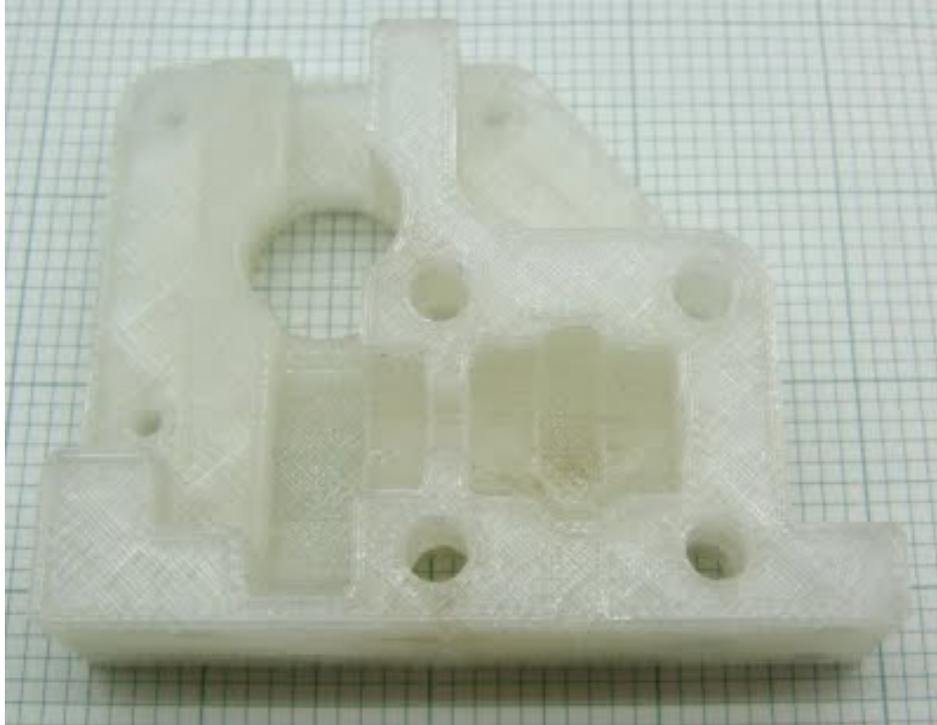
As the worm gear is about twice the diameter of the threaded pulley the axial force on the motor is about half the force required to push the filament, i.e. a few kilograms. After making a few objects it cracked along the layer where the bearing housing rises out of the flat motor mount.

I designed a new bracket but I was back in a chicken and egg situation with no working extruder to print it. As Erik pointed out you need a [Robin Hood / Friar Tuck strategy](#) of having two machines so that one can make replacement parts for the other. I must get my Darwin up and running!

In the meantime I cobbled it back together with some random bits of metal, some tiny G-clamps and tie wraps: -



I made some of the new bracket thicker where I could: 8mm instead of 5mm, which should be ~2.5 times stronger. I also added some ribs and extruded it at 10°C higher temperature.



This one seems solid as a rock, but it did warp a little more. The stronger you make something the more it warps.

Here is a video of it not flexing: -

# Pinchless Extruder

Monday, 30th November 2009 by Nophead

While dismantling my extruder for a small mod I accidentally discovered that the worm pulley has so much grip that it will still extrude PLA with the pressure roller removed. It is hard to see on this low quality video but it was extruding 0.4mm filament at 32mm/s.

I will still run it with a roller because it helps to guide it into the tube when self feeding to start a new filament. I also expect softer plastics would need it.

BTW, I have stopped using Vimeo and gone back to YouTube because they added an artificial processing delay unless you pay.

# Quality control

Friday, 4th December 2009 by Nophead

I RepRapped a doorstop for our new bathroom shower: -



It has a 10mm hole most of the way down and a countersink to take a ~5mm wood screw.

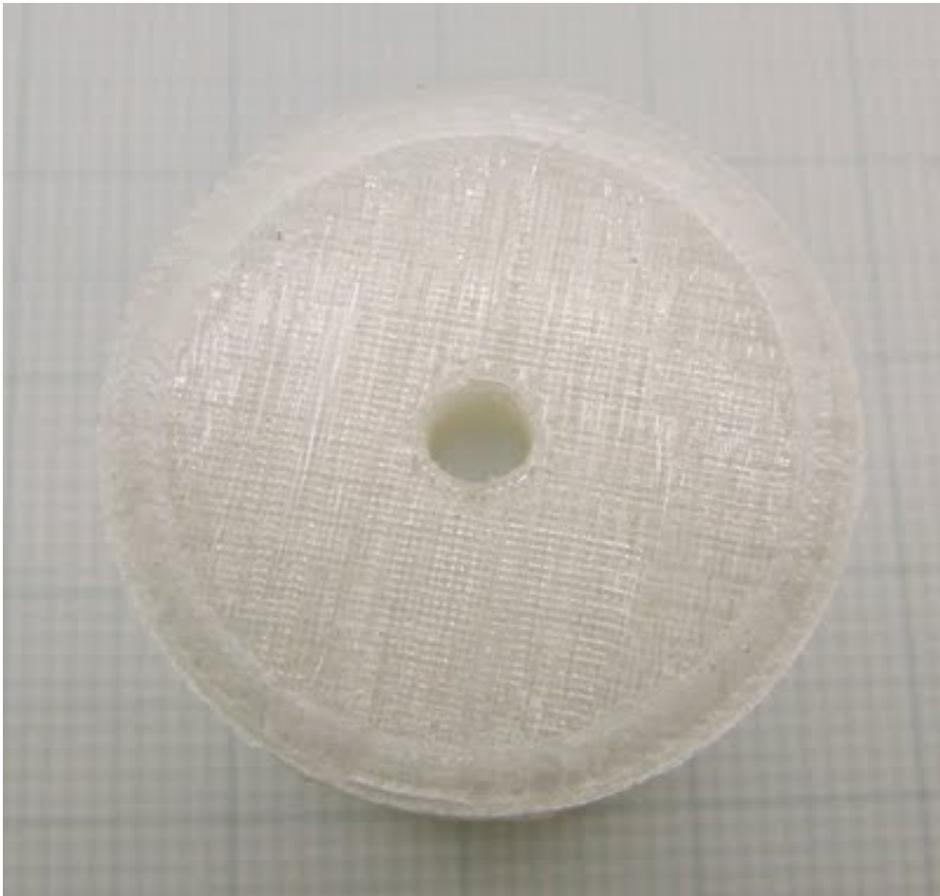


A 2mm self adhesive felt pad covers the screw hole and acts as a shock absorber.

It has a rim around the bottom to prevent it rocking if the base warps or the wall is not flat. To support the bottom of the hole there is a one layer membrane: -



I removed it with a 5mm drill: -



I was quite proud of it but my wife had something more like this in mind: -



I can't print chrome yet, so I will have to go out and buy one, and it has three screws which have to be drilled through the tiles into the wall.

The files are on [Thingiverse](#) if you prefer function over form.

# Motoring on with the A3977

Sunday, 13th December 2009 by Nophead

Previously I have blogged about how to set up the Allegro A3977 driver chip to suit a particular motor: -

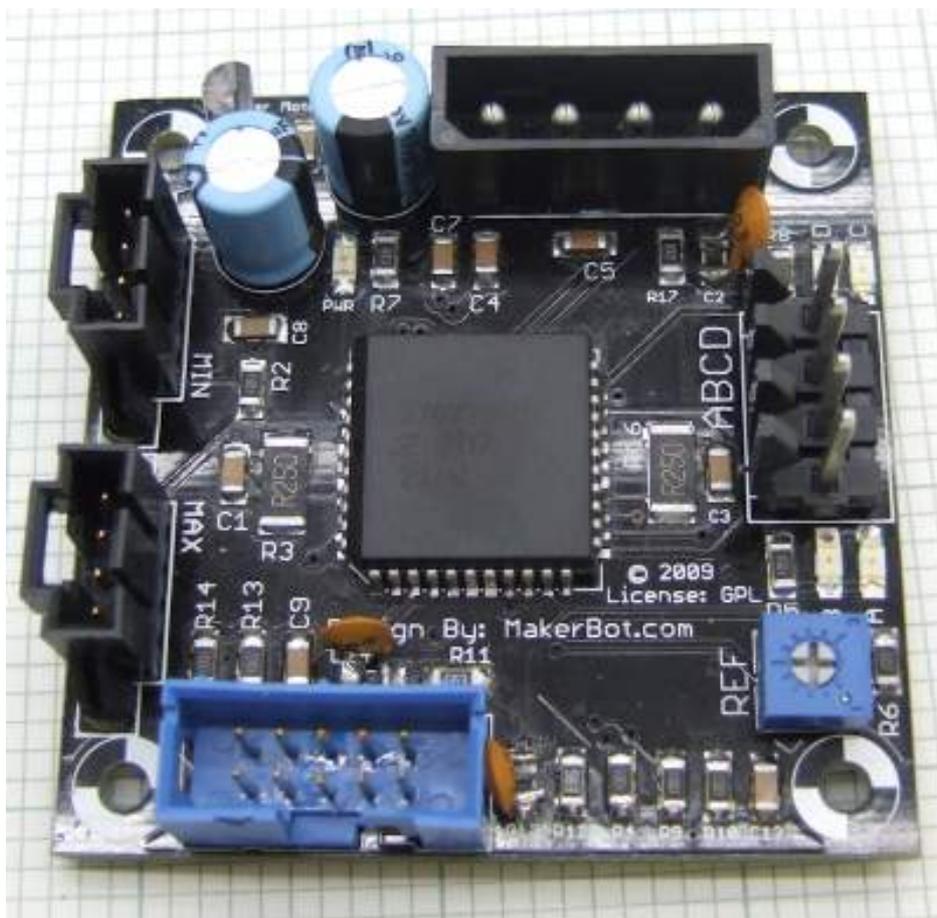
[hydraraptor.blogspot.com/2009/07/lessons-from-a3977](http://hydraraptor.blogspot.com/2009/07/lessons-from-a3977)

[hydraraptor.blogspot.com/2009/08/motor-math](http://hydraraptor.blogspot.com/2009/08/motor-math)

[hydraraptor.blogspot.com/2009/08/mixed-decay-mixed-blessing](http://hydraraptor.blogspot.com/2009/08/mixed-decay-mixed-blessing)

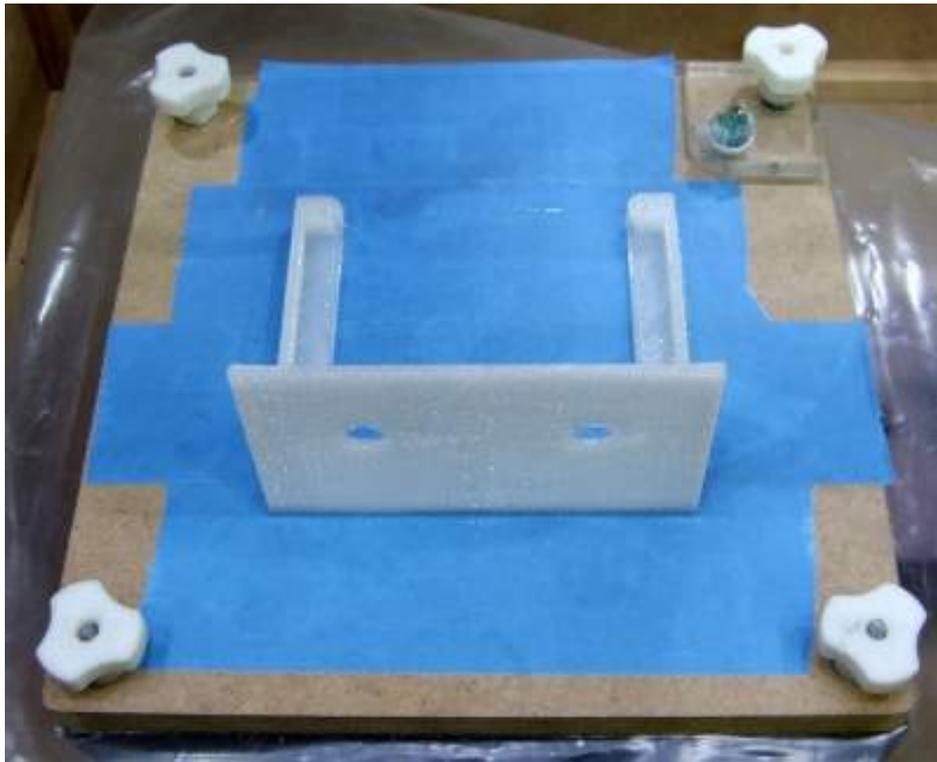
Most boards I have seen using the A3977 and similar chips just have a current adjustment, with all the other values fixed. Unless you strike lucky this is not going to allow accurate microstepping because the off time and PFD need to be adjusted to suit the motor and supply voltage.

A while ago Zach sent me samples of the prototype V3 stepper controller kits and the NEMA17 motors used on the MakerBot. I made up the board using my SMT oven (pizza oven controlled by HydraRaptor, more on that later).

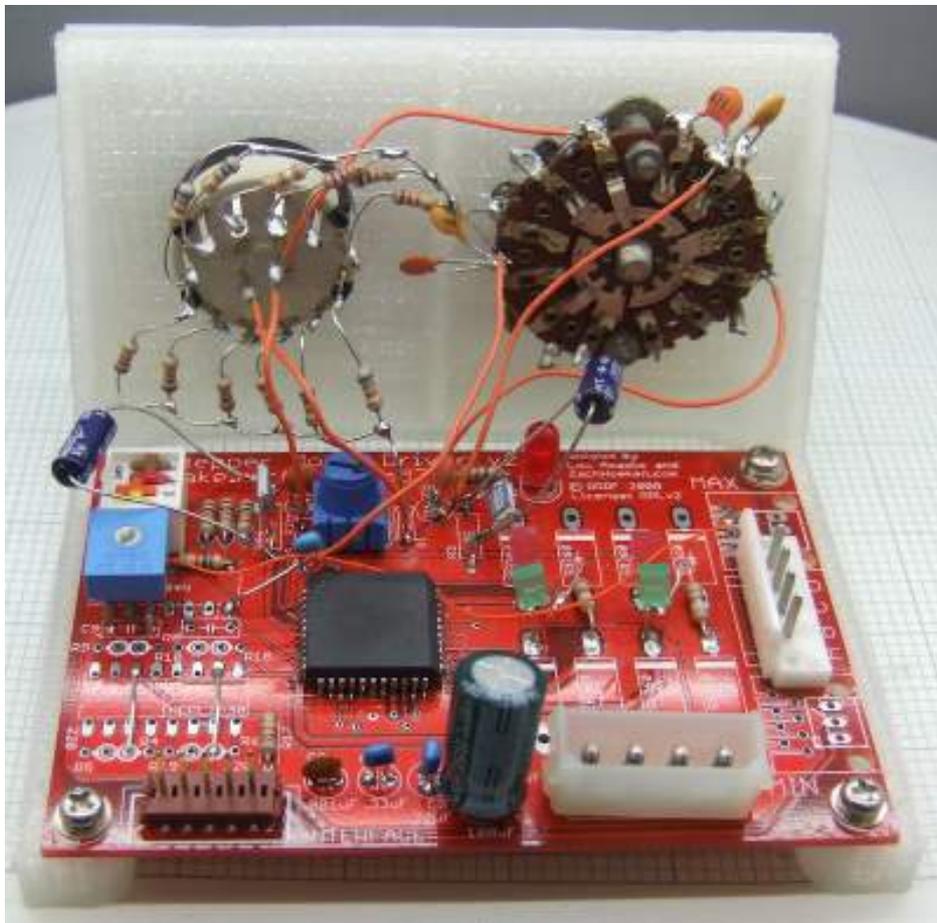


It works well, but the initial component values are not optimum for the motor, so I decided to make a test bench from the older prototype board that I have been experimenting with. I RepRapped a

chassis for it with a panel to mount some switches to vary the timing components.



The chassis is one of the biggest parts I have made, not in volume, but in overall expense. It warped a little, despite being PLA, heated bed coming soon!



The switch on the left must be at least 20 years old and the one on the right more than 40 but they both still work fine. I save all this junk and eventually it comes in handy.

I also have potentiometers on  $V_{ref}$  and PFD, so together with a bench PSU and a signal generator I can vary every parameter.

I knocked up a label on a 2D printer, it's so much easier to make this sort of thing than it was when the switches were born!

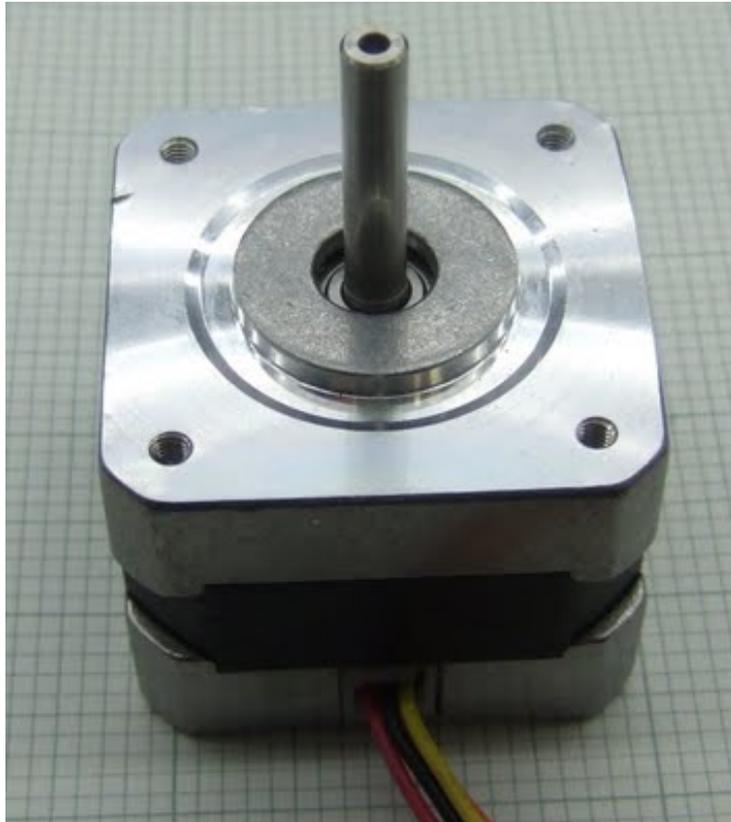


Zach has updated the board to have four preset potentiometers to make it fully adjustable. There are test points to allow the pots to be set to prescribed values with a multi-meter.

$V_{ref}$  and PFD can be measured as a voltage, but the two RT values have to be set by measuring resistance with the power off. My multimeter seems to give accurate readings of these despite them being in circuit. A good tip is to measure the resistance with both polarities and if it reads the same either way round then it is most likely the chip is not affecting the reading.

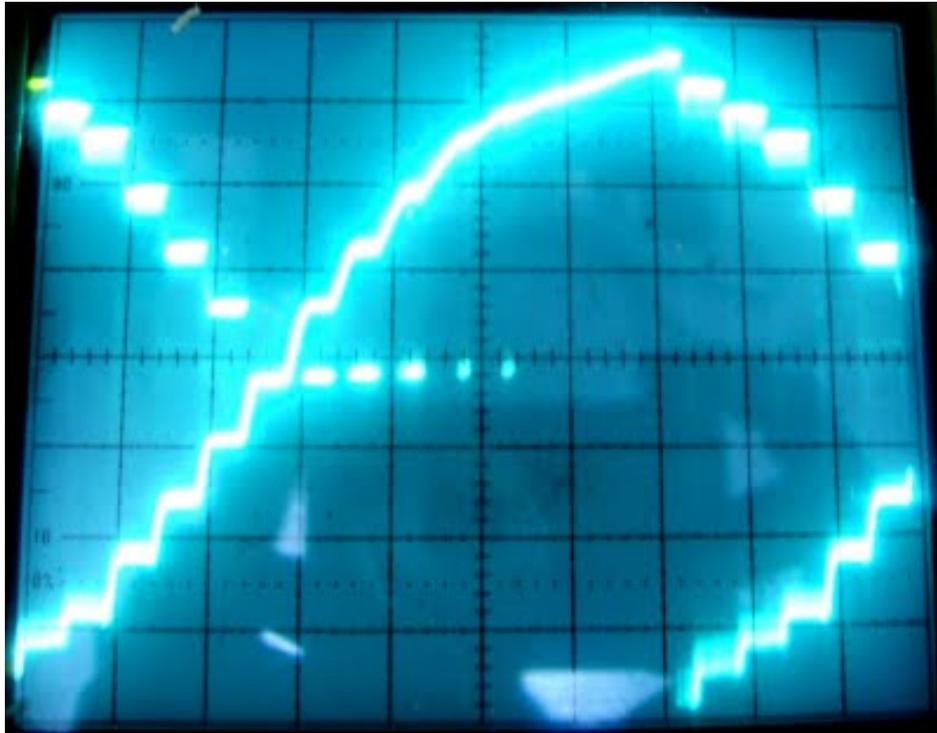
So here is a list of motors and optimised settings: -

**MakerBot Kysan SKU1123029 NEMA17**



This is the motor that MakerBot use for the axis drive on the Cupcake, details [here](#). It is actually a 14V motor, so is not ideally suited to being driven from a 12V chopper drive. You normally want the motor voltage to be substantially lower than the supply.

You can't run it at its full current because the duty cycle would tend to 100%. With a fixed off-time, the on-time tends towards infinity and the frequency drops into the audio range. In practice I found the maximum current at 12V was 0.3A, any higher and the microstepping waveform was distorted on the leading edge due to the current not being able to rise fast enough.



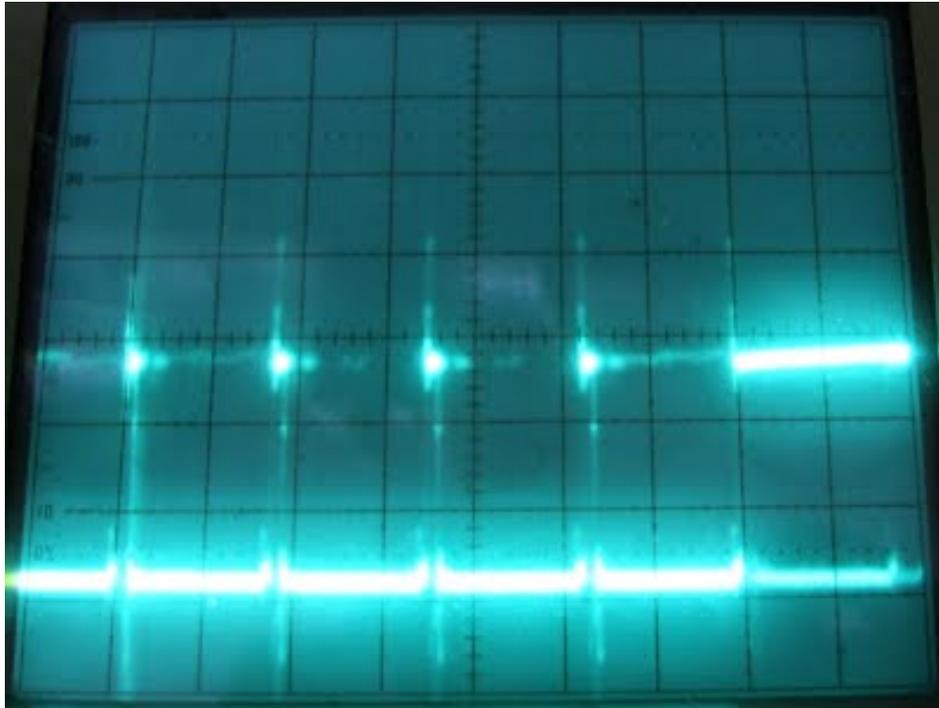
To maintain the sinusoidal waveform at faster step rates requires the current to be lowered further, 0.25A gives a good compromise. It is not a bad idea to under run steppers anyway, otherwise they can get too hot for contact with plastic.

I used the minimum values for CT and RT, i.e. 470pF and 12K to keep the chopping frequency as high as possible, so that it is outside of the audio range. Not only is this a good idea to keep it quiet when idling, but also you want it much higher than your stepping frequency, otherwise they beat with each other.

The values give a minimum frequency of ~17kHz @ 0.3A and a maximum of ~150kHz on the lowest microstep value. 17kHz is not audible to me, but younger people might be able to hear it. There is still some audible noise at the point in the cycle when both coils have similar currents and so similar high frequencies. The beat frequency, which is the difference of the two, is then in the audio range. It isn't anywhere near as loud as when the chopping is in the audio range though.

I can't see any spec for the maximum switching frequency although a couple of parameters are given at less than 50kHz. I suspect 150kHz is a bit on the high side, which would increase switching losses, but with such a low current compared to the rating of the chip I don't think it is a problem.

One problem I had initially was that the switching waveform was unstable. It had cycles with a shorter on-time than required, which let the current fall until it then did a long cycle to catch up. The long cycle gave a low frequency that was back in the audio range.



I think it was a consequence of the motor needing a very short off-time in order to be able to have the duty cycle nearly 100%. The current hardly falls during the off period, so a little noise due to ringing can trigger it to turn off too early. It is not helped by using the minimum blank time. I fixed it by putting 1uF capacitors across the sense resistors.

The PFD value is best set to 100% fast decay with this motor.

It works better with a 24V supply. The full 0.4A current can be achieved (but it gets much hotter of course) and it maintains microstepping accuracy at higher step rates than it does on 12V.

**MakerBot Lin SKU4118S-62-07 NEMA17**



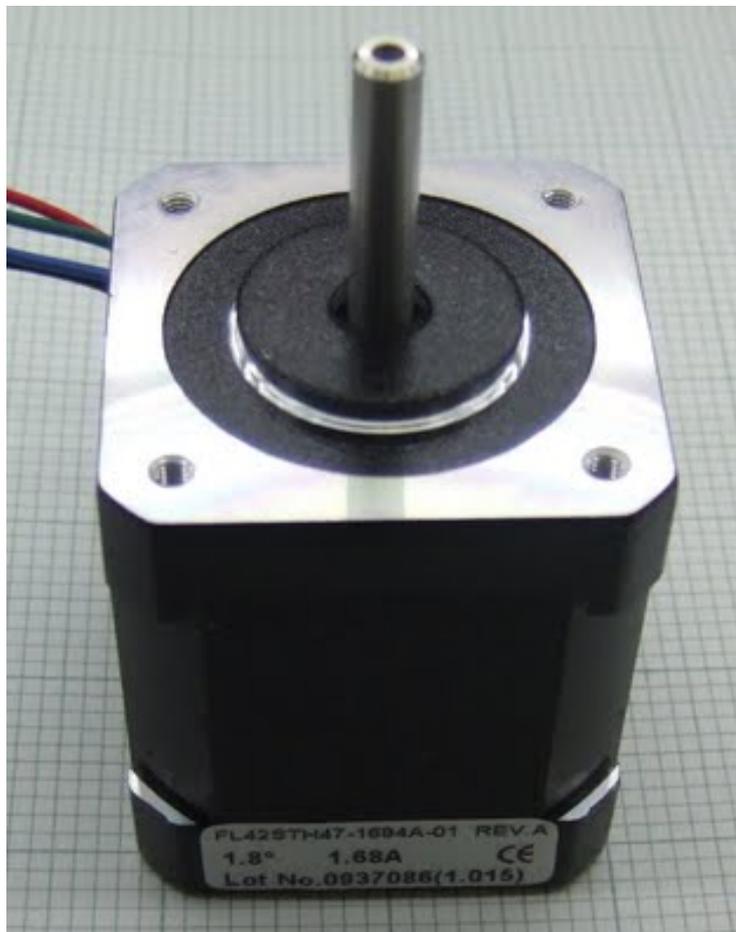
This is the NEMA17 that MakerBot used to supply. It is at the opposite extreme compared to the one above, i.e. it is a very low voltage motor, only 2V @ 2.5A. As mentioned before, this causes a couple of issues: -

1. The inductance is so low that the ripple current is significant compared to the lowest current microstep, causing positional errors. OK at 2A, but gets worse with lower currents.
2. It is difficult to get 2.5A from the A3977 without it overheating. The PCB layout has to be very good. The datasheet recommends 2oz copper and four layers. 2A is no problem and that is the maximum with the 0.25 sense resistors fitted to the board.

At 2A the motor runs at about 40°C, so just about OK for use with PLA. The chip gets a lot hotter, about 77°C measured on the ground pins.

I used a value of 56K for RT and 2.1V on PFD. To some extent the optimum PFD value depends on how fast you want it to go.

## Motion Control FL42STH47-1684A-01 NEMA17



This is the recommended motor for the Mendel extruder, details [here](#). After buying a couple of these a friend pointed out that [Zapp Automation](#) do the same motor with dual shafts for about half the price!

This is a high torque motor so it is longer and heavier than the previous two NEMA17s. Electrically it is in the sweet spot for the A3977 with a 12V supply. The A3977 can easily provide the full current and the switching frequency doesn't have wild fluctuations or drop into the audio range.

When microstepped at 1.7A it gets to about 43°C but the chip only gets to 56°C.

I used 39K for RT and 0V on PFD, i.e. 100% fast decay.

I have high hopes for this motor as a replacement for the one above that is in my extruder currently. It should give me almost twice the torque and has the correct sized shaft, i.e. 5mm. The Lin and Kysan motors both have imperial shaft sizes which caught me out as I drilled the worm gear for 5mm thinking NEMA17 specified that, but it must just be the frame dimensions.

## MakerBot Keling KL23H251-24-8B NEMA23



This is the motor I used on my Darwin. It has 8 wires so it can be connected in bipolar serial or parallel. Series has the advantage that the full torque can be achieved with 1.7A which is easily within the range of the A3977. Parallel has one quarter of the inductance so torque will fall off with speed four times slower. To get full torque 3.4A is needed but I found 1A was enough for the X and Y axes. I think Z needs more torque but my z-axis uses different motors so I don't know how much.

An RT value of 56K is fine for currents in the range 1-2A. PFD is best at 0v, i.e. 100% fast decay.

## Summary

Here is a summary of the motor specifications :-

<u>Motor</u>	<u>Resistance</u>	<u>Max Current</u>	<u>Voltage</u>	<u>Max Power</u>	<u>Holding Torque</u>	<u>Inductance</u>
LIN 4118S-62-07	0.8 Ohm	2.5 A	2.0 V	10.0 W	0.30 Nm	
Kysan SKU 1123029	35.0 Ohm	0.4 A	14.0 V	11.2 W	0.26 Nm	44.0 mH
Motion Control FL42STH47-1684A-01	1.7 Ohm	1.7 A	2.8 V	9.5 W	0.43 Nm	2.8 mH

Keling

KL23H251- 3.6 Ohm 1.7 A 6.1 V 20.8 W 1.10 Nm 13.2 mH  
24-8B Series

MakerBot

Keling

KL23H251- 0.9 Ohm 3.4 A 3.1 V 20.8 W 1.10 Nm 3.3 mH  
24-8B  
Parallel

Here are my suggested settings :-

<u>Motor</u>	<u>Current</u>	<u>Vref</u>	<u>CT</u>	<u>RT</u>	<u>PFD</u>
Kysan SKU 1123029	0.25 – 0.3A	0.5 – 0.6V	470pF	12K	0
LIN 4118S-62- 07	1 – 2A	2 – 4V	470pF	56K	2.1V
Motion Control FL42STH47- 1684A-01	1 – 1.7A	2 – 3.4V	470pF	39K	0
Keling KL23H251-24- 8B Parallel	1 – 2A	2 – 4V	470pF	56K	0

# Reliable extruder at last?

Monday, 21st December 2009 by Nophead

... well only time will tell but I have now fixed all the teething problems on my "no compromise" extruder.

The first problem was it was leaking plastic. I simply tightened the thread about another quarter turn while hot. The problem started when I had to dismantle it to replace the first resistor that I damaged. When I put it back together I didn't get it tight enough as it is difficult to judge when full of plastic and hot. The seal relies on the fact that the relatively sharp edge of the stainless steel tube can bite into the softer aluminium. It seems to work when tightened enough.

The other problem was that the motor would skip steps in the middle of a build for no apparent reason. It seems the amount of force required to extrude varies wildly for which I have no explanation, but I did find some mechanical issues that were reducing the torque available.

I noticed the gear would always be in the same position when the motor skipped. I found that the grub screw was catching on the bearing housing. You would expect it just to grind the PLA away, but PLA is very hard, so it would take a very long time to do so. I increased the clearance around the wheel hub and also around the moving part of the ball bearings.

Another issue was that both the worm and the gear were slightly off centre on their shafts, so when the two high points coincided they would bind. The hole in the Meccano gear is slightly bigger than the 4mm shaft it is on, not sure why. The hole I drilled in the worm is 5mm but the MakerBot motors have imperial shafts about 4.75mm, so that was even more eccentric. Added to that was the fact that the motor bracket has a slight warp to it angling the shaft down a little. All these things conspired to make it stiff to turn once per revolution. I fixed it by tightening the bottom motor screw tight and slackening the top two a little. That was enough to reliably extrude PLA. Making the motor holes into slots would make things less critical.

Although the extruder was working reliably for PLA I wanted more torque in reserve, so I switched to a higher torque motor more suited to my driver chip. The Lin motor I was using was rated at 0.3Nm holding torque for 2.5A, but my controller can only manage about 1.5A without some better heatsinking. I switched to the Motion Control FL42STH47-1684A-01 which gives 0.43Nm at 1.7A. So at 1.5A I have gone from 0.18Nm to 0.4Nm, i.e. doubled the torque and also got the right shaft diameter to fit the hole I drilled in the worm.



The only downside is that it is bigger and heavier, not really an issue on HydraRaptor.

To give it a thorough test I printed off a couple of Mendel frame vertices.



These take about 2 hours each with 0.4mm filament, 25% fill, double outline at 16mm/s, infill at 32mm/s. Six are needed in total.

I still have to test it with HDPE and PCL., I know it works with ABS.

# Cooking with HydraRaptor

Tuesday, 29th December 2009 by Nophead

I needed to assemble some PCBs recently, so I set about making a temperature controller for my SMT oven.



First I had to replace the solid state relay on HydraRaptor.



Solid state relays are triacs with an optically coupled input, zero crossing switching and built in snubbers. I used it for controlling a vacuum cleaner when milling. It was massively overrated but for some reason it failed some time ago. I replaced it with a cheaper one and added a varistor across the mains input to kill any transients, as that is the only explanation I can think of for the old one's demise.



The next task was to write a simple graphing program in Python. I tested it by plotting the response of my extruder heater.



With bang-bang control it swings  $\pm 2^{\circ}\text{C}$  with a cycle time of about ten seconds.

Here is the code for the graph: -

```
from Tkinter import *

class Axis:
    def __init__(self, min, max, minor, major, scale):
        self.scale = scale
        self.min = min
        self.max = max
        self.minor = minor
        self.major = major

class Graph:
    def __init__(self, xAxis, yAxis):
        self.xAxis = xAxis
        self.yAxis = yAxis
        self.root = Tk()
        self.root.title("HydraRaptor")
        self.last_x = None
        frame = Frame(self.root)
        frame.pack()
        xmin = xAxis.min * xAxis.scale
```

```

xmax = xAxis.max * xAxis.scale
ymin = yAxis.min * yAxis.scale
ymax = yAxis.max * yAxis.scale
width = (xmax - xmin) + 30
height = (ymax - ymin) + 20

#
# X axis
#
self.canvas = Canvas(frame, width = width, height = height, background = "white")
for x in range(xmin, xmax + 1, xAxis.minor * xAxis.scale):
    self.canvas.create_line(x, ymin, x, ymax, fill = "grey")
for x in range(xmin, xmax + 1, xAxis.major * xAxis.scale):
    self.canvas.create_line(x, ymin, x, ymax, fill = "black")
    if x == xmin:
        anchor = "nw"
    else:
        anchor = "n"
    self.canvas.create_text((x, ymax), text = x / xAxis.scale, anchor = anchor)

#
# Y axis
#
for y in range(ymin, ymax + 1, yAxis.minor * yAxis.scale):
    self.canvas.create_line(xmin, y, xmax, y, fill = "grey")
for y in range(ymin, ymax + 1, yAxis.major * yAxis.scale):
    self.canvas.create_line(xmin, y, xmax, y, fill = "black")
    if y == ymin:
        anchor = "se"
    else:
        anchor = "e"
    self.canvas.create_text((xmin, ymax + ymin - y), text = y / yAxis.scale, anchor =
anchor)

self.canvas.pack()
self.canvas.config(scrollregion=self.canvas.bbox(ALL))
self.root.update()

def scaleX(self,x):
    return x * self.xAxis.scale

def scaleY(self,y):
    axis = self.yAxis;
    return (axis.max + axis.min - y) * axis.scale

```

```

def plot(self, line, colour = "blue"):
    for i in range(len(line) - 1):
        self.canvas.create_line(self.scaleX(line[i][0]),
                                self.scaleY(line[i][1]),
                                self.scaleX(line[i+1][0]),
                                self.scaleY(line[i+1][1]), fill = colour)

    self.root.update()

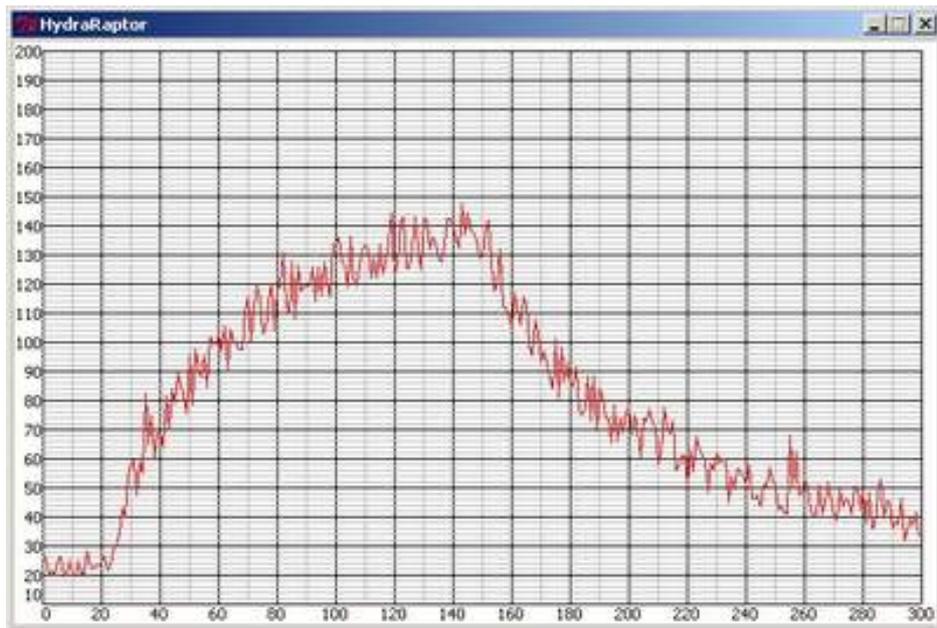
def addPoint(self,p, colour="red"):
    x = self.scaleX(p[0])
    y = self.scaleY(p[1])
    if self.last_x != None:
        self.canvas.create_line(self.last_x, self.last_y, x, y, fill = colour)

    self.last_x = x
    self.last_y = y
    self.root.update()

def __del__(self):
    self.root.mainloop()

```

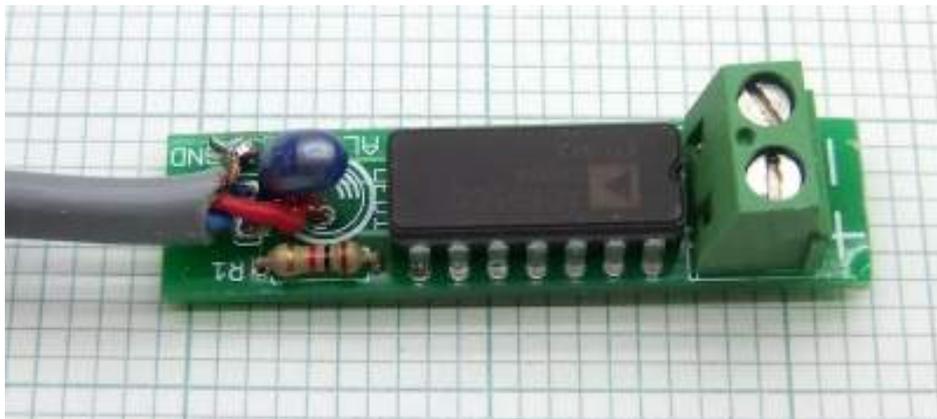
The third task was to interface a thermocouple to HydraRaptor. I had a spare analogue input, so I attached one of Zach's thermocouple sensor boards to it. I tested it by attaching the thermocouple to a light bulb with Kapton tape. I then ran a program that turned the bulb on and then off and graphed the temperature response.



As you can see there is a ridiculous amount of noise on the readings. I tracked this down to

switching noise on HydraRaptor's 5V rail, which is generated by a simple buck converter from a 24V rail. The AD595 datasheet claims that it has a power supply sensitivity of only 10mV/V so the error should have been a small fraction of a °C. All I can assume is that its rejection of high frequency noise is far less than its DC supply rejection. In fact, pretty much all the supply noise appears on the output.

I fixed it by filtering the supply with a simple RC filter consisting of a 1K series resistor and a 22uF capacitor. I fitted these to the thermocouple board in the unused holes intended for an alarm LED and its series resistor. The power is fed in via the anode connection for the LED. It feeds to the supply rail via the 1K fitted in the R1 position. The positive lead of the capacitor goes into the original +5v connection to the board. The negative lead goes to the GND connection together with the ground lead. This mod will be required whenever the 5V rail comes from a switch mode supply rather than a linear regulator.



Here is the much improved graph with the filter fitted: -



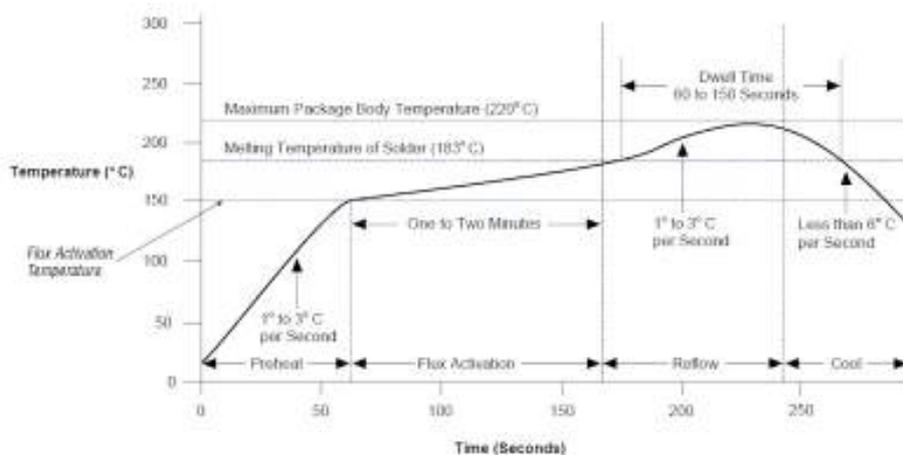
The next thing I tried was bang-bang control of the oven to a fixed temperature with the thermocouple attached to a scrap PCB. No great surprise that there is massive overshoot due to

the thermal lag caused by the loose coupling of the PCB to the heating elements via air.



It is obvious some form of proportional control is required, so I implemented PWM control of the mains supply to the oven. As triacs don't turn off until the end of the mains cycle there is no point in varying the pulse width in less than 10ms increments (in the UK). So I implemented a simple firmware scheme where I can specify how many 10ms units to be on for out of a total period, also specified in 10ms units. Setting the period to 1 second allows the heating power to be expressed in 1% units.

My original plan was to implement a PID controller, but after examining the required soldering profile I decided a much simpler scheme would probably perform better.



This is a profile for tin-lead solder that I got from an [Altera application note](#). I mainly use leaded solder at home because the lower melt point gives a much bigger margin for error, it wets and flows a lot better, the fumes are less toxic and it doesn't grow tin whiskers.

Looking at the profile you can see the times are not too critical, but the temperatures are. I reasoned I could simply apply fixed powers to get the right temperature gradient until each target temperature was reached. To get round the overshoot problem I simply measured the overshoot and subtracted it from the target temps.

After a little experimenting I got this profile, which looks pretty good to me: -



The blue line is the target profile, red is actual and the green lines show the time at which each target was reached.

The preheat slope and re-flow slope are simply full power until the temperature is equal to the target minus the overshoot. During the first half of the soak period I had to ramp the power from 0 to 50% to get it to turn the first corner without overshoot. When the reflow peak minus the overshoot is reached I simply turn the oven off. When it gets to the cool section I open the oven door.

Here is the code: -

```

from Hydra import *
from Graph import *

profile = [(10,20), (120,150), (210,180), (250,210), (330, 180), (420, 20)]

slope = 140.0 / 100
overshoot = 15.0
pre_overshoot = 25

preheat_temp = 150.0
soak_temp     = 180.0
soak_time     = 90.0
reflow_temp   = 210.0
melt_temp     = 183.0

```

```

preheat_slope = (soak_temp - preheat_temp) / soak_time

s_preheat = 1
s_soak = 2
s_reflow = 3
s_cool = 4

def interp(profile, x):
    i = 0
    while i < len(profile) - 1 and profile[i + 1][0] < x:
        i += 1
    if i == len(profile) - 1:
        return 0
    p0 = profile[i]
    p1 = profile[i+1]
    return p0[1] + (p1[1]-p0[1]) * (x - p0[0]) / (p1[0] - p0[0])

def oven_cook(profile):
    hydra = Hydra(True)
    try:
        xAxis = Axis(min = 0, max = 500, minor = 5, major = 25, scale = 2)
        yAxis = Axis(min = 10, max = 250, minor = 5, major = 20, scale = 2)
        graph = Graph(xAxis, yAxis)
        graph.plot(profile)

        t = 0
        state = s_preheat
        m_state = s_preheat
        hydra.set_mains(100,100)
        while t < xAxis.max:
            sleep(1)
            temp = hydra.get_temperature()
            print temp
            graph.addPoint((t, temp))
            #
            # Control the power
            #
            if state == s_preheat:
                if temp >= preheat_temp - pre_overshoot:

```

```

        hydra.set_mains( 0, 100)

        t_soak = t

        state = s_soak
elif state == s_soak:

    power = (t - t_soak) * 100.0 / soak_time

    if power > 50:

        power = 50

    hydra.set_mains(int(power), 100)

    if temp >= soak_temp - overshoot * preheat_slope / slope:

        hydra.set_mains(100,100)

        state = s_reflow
elif state == s_reflow:

    if temp >= reflow_temp - overshoot:

        hydra.set_mains(0,100)

        state = s_cool

#

# Draw the time lines

#

if m_state == s_preheat:

    if temp >= preheat_temp:

        graph.plot([(t,10), (t,temp)], "green")

        m_state = s_soak
elif m_state == s_soak:

    if temp >= melt_temp:

        graph.plot([(t,10), (t,temp)], "green")

        m_state = s_reflow
elif m_state == s_reflow:

    if temp < melt_temp:

        graph.plot([(t,10), (t,temp)], "green")

        m_state = s_cool

    t += 1

hydra.init()

except:

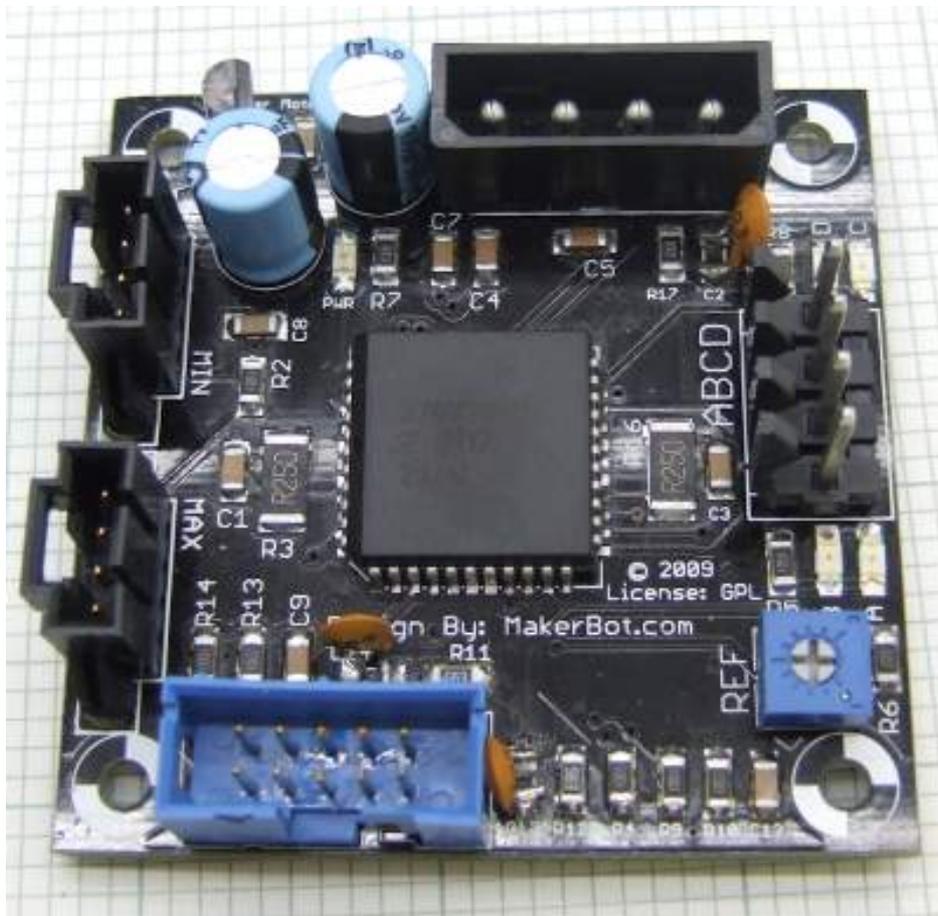
    hydra.init()

    raise

oven_cook(profile)

```

This is the first board I soldered with it: -



All the joints were good. I had a few solder balls and some bridging but that was due to not getting the right amount of paste on each pad. I will be working on a solder paste dispenser soon!

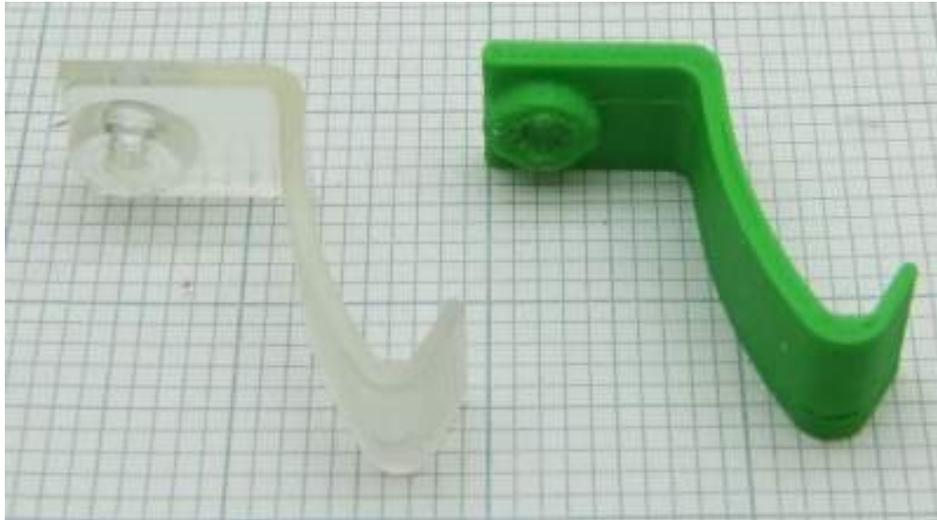
I need to do some more testing to see if the arbitrary algorithm will work with large and small boards and with inner planes, etc. It relies on the overshoot being fairly constant, although with leaded solder you have some leeway.

I also want to play with PID to see if I can get a more general solution. The problem I see is that PID does not look into the future, so will always overshoot somewhat, which is exactly what you don't want. I think rather than using the angular profile, that is impossible for the oven to follow, I would have to put in a rounded curve, such as the one the oven actually follows now, as the control input.

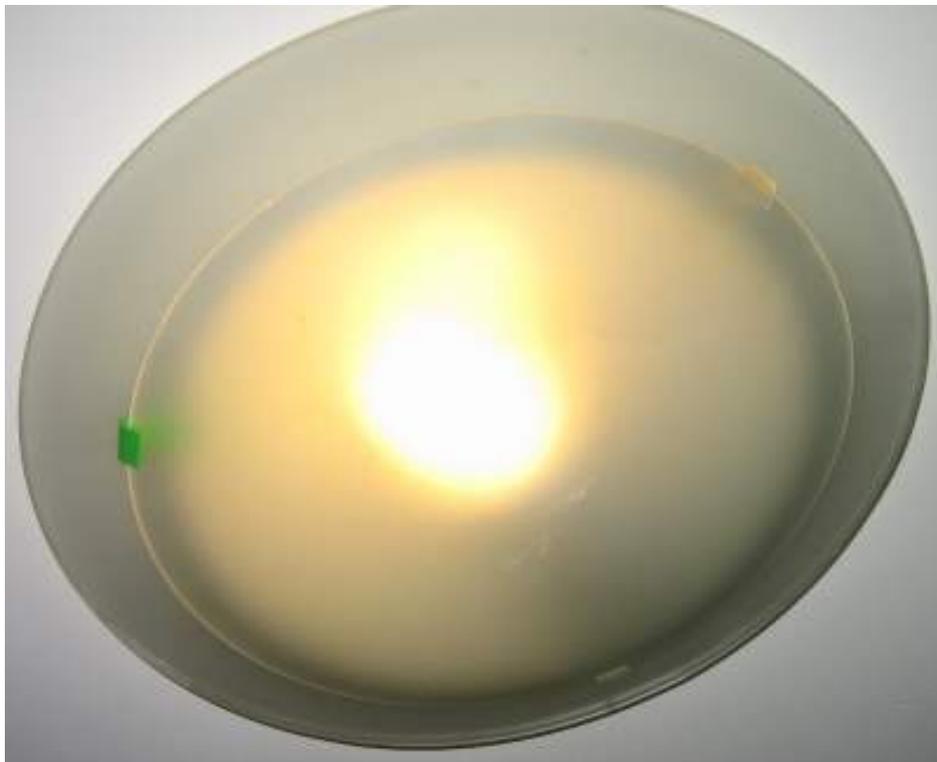
# New Year New Plastic

Friday, 1st January 2010 by Nophead

Just over a year ago a friend asked me to make replacement for a broken clip that was part of a light fitting. It was not too difficult to model and I made a copy in ABS with 0.3mm filament, 0.24mm layers.



It did the job mechanically, but with one obvious aesthetic problem: -



The original clips were made from transparent polycarbonate and all I had at the time was green ABS. I didn't use PLA because I worried the lamp could easily get hot enough for the clip to go soft

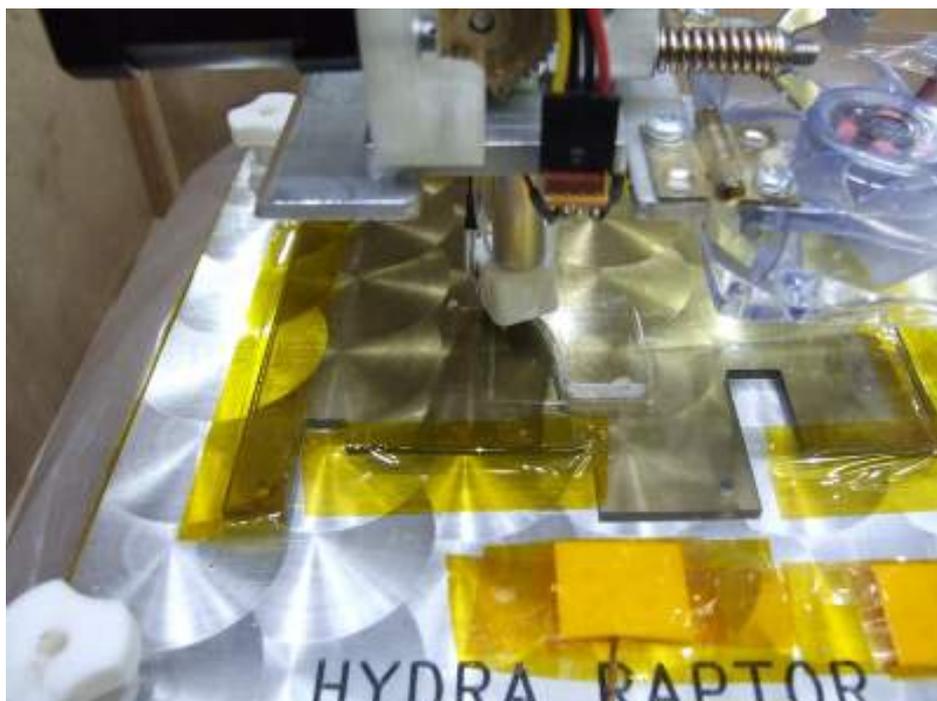
and drop the shade. The only transparent thermoplastic that I could get hold of in filament form was PMMA (AKA acrylic / Perspex, etc), which is available in 1m rods. It is too stiff and brittle to use in my previous extruder, so I promised to have a go when I moved to a pinch wheel design.

The first attempt was a complete failure. It melts at 130 - 140 or 165°C depending where you read. It has a relatively high glass transition, 100-114°C, again depending where you read. I found I could extrude it with a fair amount of force at 180°C. It is very viscous with plenty of die swell. I couldn't get it to stick to anything, including itself, at that temperature though. It isn't sticky like PLA, so it wouldn't stick to masking tape. The obvious second choice was a sheet of acrylic as all thermoplastics will stick to themselves.

The general rule of thumb to make plastic weld to itself is that the average of the temperature of the hot part and the cold part has to be higher than the melting point. So to get it to stick to the base, which is at room temperature it would have to be extruded at twice the melting point minus the ambient temperature. The only plastic that seems to break this rule is PLA which melts at 160°C but will bond to itself at 180°C. I think it is something to do with it having a low glass transition and / or that it is sticky like a glue when it is molten.

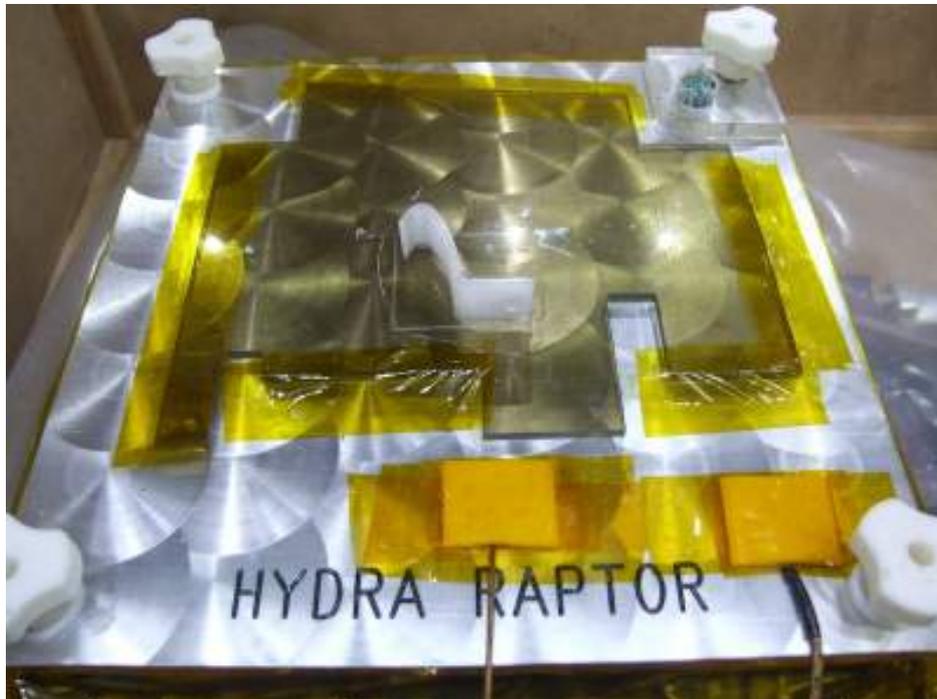
I upped the temperature to 240°C but it started to hiss and smoke and still did not bond to the base. Lots of places quote the boiling point of PMMA to be 200°C! I dropped the temperature back to 220°C and it is much happier, but still does not stick .

So the only way to make it bond with itself is to raise the ambient temperature. Cue the heated bed. I set the temperature of my aluminium plate to 100°C, the hottest it can safely be below the glass transition. I taped a small scrap of 3mm acrylic sheet to the middle of the bed with Kapton tape. From my experiments before I estimate the surface temperature would be about 85°C. That gives an interface temperature of about 150°C and that seems to be enough to get it to bond to itself.



Here is a short video of 0.3mm PMMA filament being extruded at 16mm/s: -

Here is the finished object: -



It was not too difficult to release from the bed with a penknife once the bed has cooled that is, I keep forgetting that it is hot! The bed takes ages to cool unless I blow it with a fan.

I am very pleased with the final result. I only had 1 meter of 3mm filament to get this right and I managed to find a suitable bed material, temperature settings and make three clips. The build quality is excellent even if I say it myself.



So another useful material in the RepRap arsenal. Apart from HDPE I think it has the highest

working temperature. It is very stiff and brittle though. I had a couple of jams due to it snapping where it enters the extruder barrel. The alignment is not quite right because being so hard it does not press into the worm pulley as far as other plastics. The extruder could do with an adjustment there perhaps, or a bigger entrance to the pipe.

It is a bit more transparent than PLA. It smells a bit more when it is extruded, but it is not an unpleasant smell, I would describe it as sweet and aromatic. The major downside is that it is only available in rod form, so the biggest object you can make in one go is 7 cm<sup>3</sup> and at £1.49 per meter on eBay, it is comparatively very expensive.

# Extruder broke already

Sunday, 3rd January 2010 by Nophead

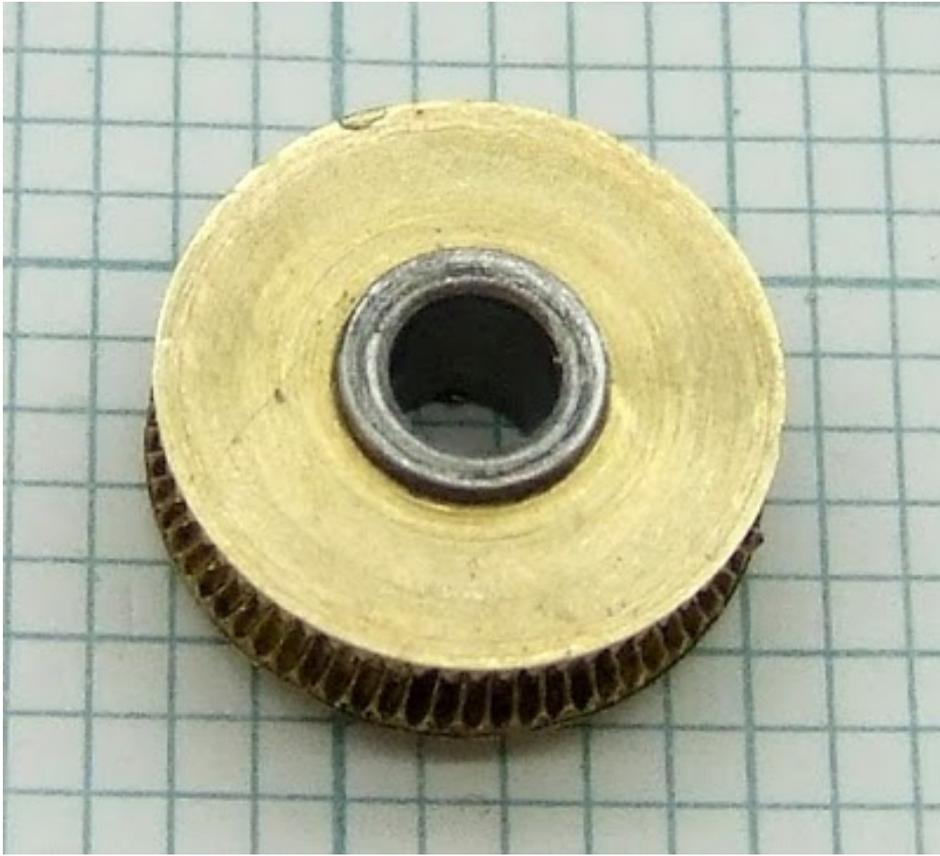
Well my best attempt at making a reliable extruder again resulted in one that only lasted a few weeks! The brass worm pulley that was pushed onto a splined shaft worked loose while extruding PMMA.



PMMA is quite hard work to extrude, but probably no worse than HDPE. On reflection splines into brass are not going to hold the massive force that occurs at 2mm radius. A better idea would be to have a boss on the side of the pulley and use a set screw onto a flat on the shaft. I would also add smaller diameter bosses at each side to meet the centre rim of the bearings. That would automatically position the pulley dead centre.

But to do that I would have to make a new pulley cutting jig and redesign the motor bracket to be a bit wider. I would need a working extruder to make the new bracket of course, so I decided to bodge the existing design.

I drilled out the centre of the pulley to 6mm and then reamed it to 6.4mm. I then turned a steel hub from a piece of hex pillar. I made it about a tenth of a millimetre oversized, added a chamfer to the hole in the pulley and forced it in with a vice, creating a very tight fit.

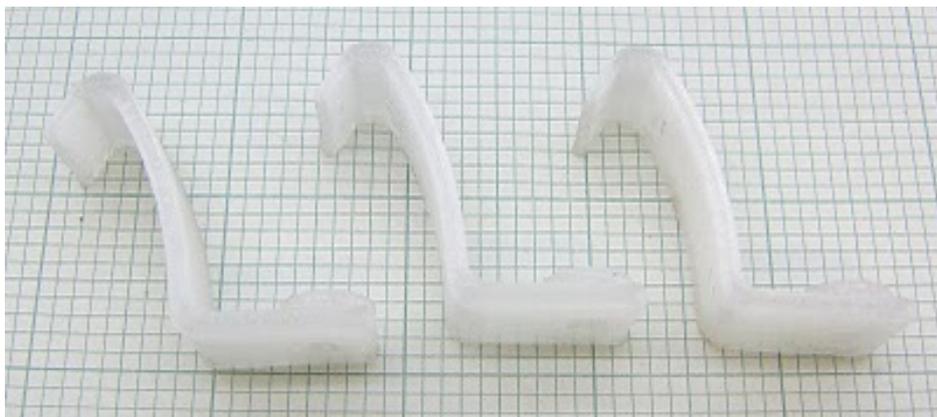


I didn't trust that to hold on its own so I left a hex flange on the other side and soldered it to the brass: -



Certainly not my best soldering, but bodging is bodging. The hub is twice as wide as the wheel and steel is harder than brass, so it should have a much better grip on the splines. I don't know if it will last or not. The constant back and forward motion of the anti-ooze fix means that if anything is weak it gets worked loose.

With the repaired extruder I made a third lamp shade clip leaving 1mm of the acrylic rod left above the pulley, how lucky is that?



Then I pushed my luck too far. When I bought the 3mm PMMA rod I also got a 2mm rod to compare results. Stiffness of a rod is a fourth power on diameter I think, so 2mm filament is five times more flexible than 3mm.



This would certainly be feasible to use in coils as it has a similar minimum bend radius to 3mm PLA, we just need to find somebody to supply it in that form at a reasonable price. 2mm rods are

even more expensive than 3mm rods, £1.24 on eBay as opposed to £1.49, but are only 44% of the volume!

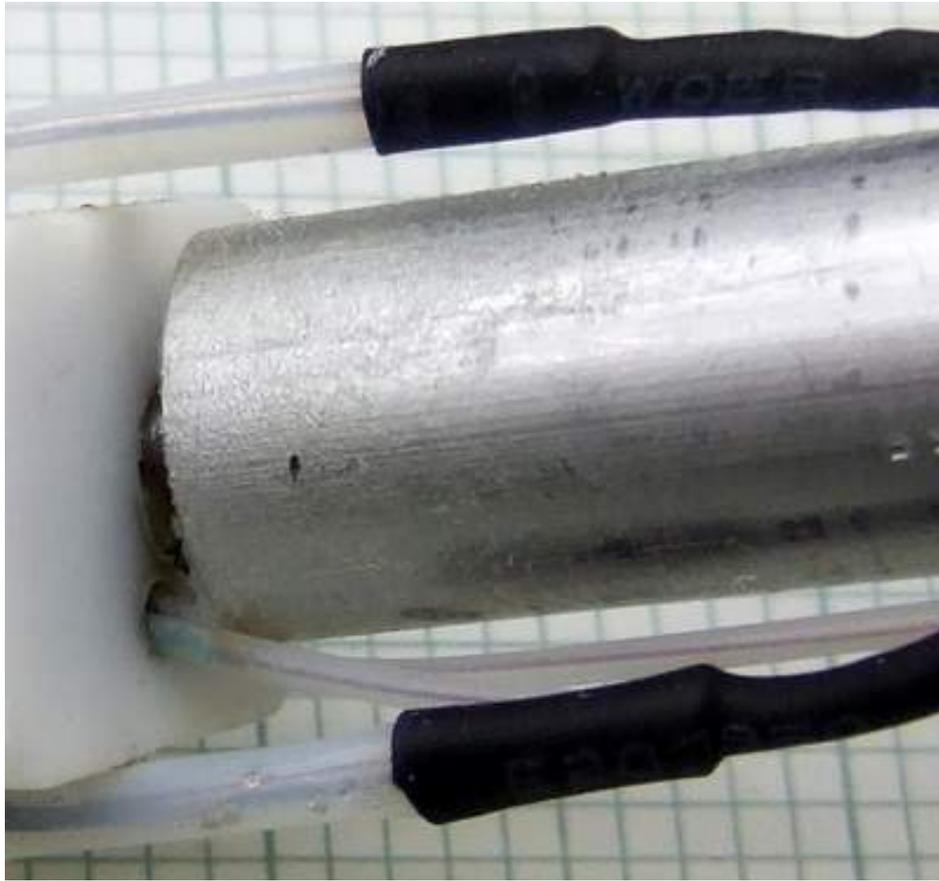
I decided to give it a try in my newly repaired extruder by printing a whistle. I had to scale it down because with 0.4mm filament it would use more than 1m of 2mm filament, so I printed the same g-code using 0.3mm filament and scaled the dimensions accordingly.

It managed to print a couple of layers and then the extruder jammed. I think the problem is that with a 3.6mm bore and 2mm filament there is too much of a gap, so molten plastic can flow upwards and freeze in the cold part of the tube above the taper. I think it would work fine with an extruder designed for 2mm filament. The drive mechanism just about works because although it does not have as much grip, it only needs 44% of the force that 3mm filament needs. The barrel and heater block would need a smaller bore though and could be made smaller. Similarly the smaller motor I used before would have plenty of torque, in fact a high torque NEMA14 should work.

So there are a lot of advantages to using 2mm feedstock like commercial machines do, BUT stiffness falls as a forth power, but force required only falls as a square law, so I expect soft plastics like HPDE, PP and PCL may buckle when being fed. Certainly the gap between the pinch wheel and the barrel entrance would need to be very small.

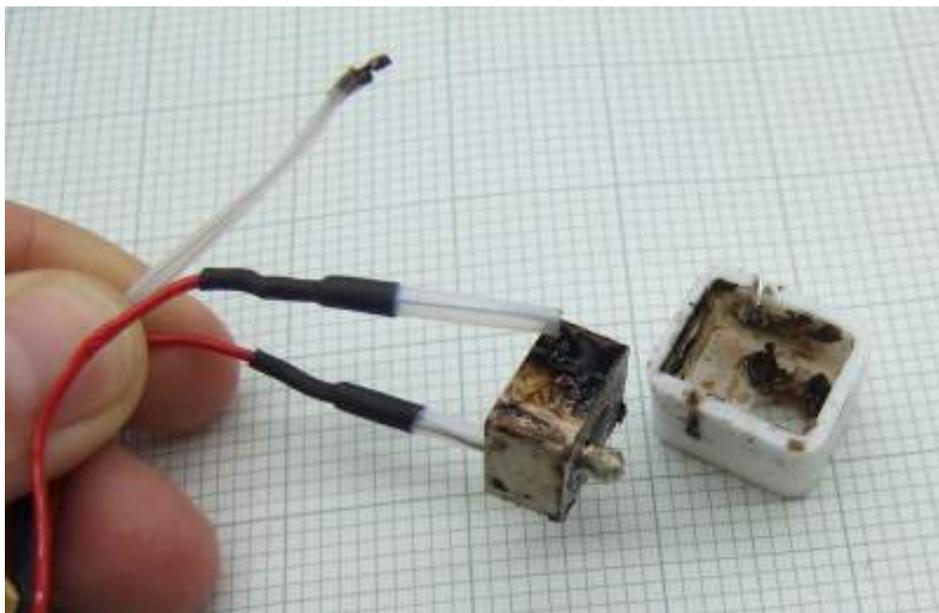
I fixed the jam by putting a drill down the hot barrel and hitting it with a hammer. That fixed it and I hand fed some ABS before reassembling the extruder. After assembly it would not work at all. The thermistor had shorted out to the metal work!

Nothing much to see from the outside, just a weird furry slimy deposit on the back of the AL tube and a green stain on the thermistor lead that was shorted.



I cannot get to the thermistor or heater without removing the PTFE cover, but that can't be removed without unscrewing the barrel, another slight design flaw. If I had tapped the stainless steel pipe all the way up I could just unscrew it from the AL tube that surrounds it, but it is really hard work tapping stainless steel.

I unscrewed the barrel while the extruder was hot to reveal this mess: -



The plastic that leaked when I first built the extruder has been stewing for weeks and has boiled

down to something resembling bitumen. I expect the more volatile products condensed on the cold AL tube above it forming the Vaseline like deposit.

I couldn't tell why the thermistor was shorted because it came away with the PTFE cover. The Cerastil that I glued it in with seems to have decomposed in the chemical soup around it. My last few attempts at sticking thermistors with Cerastil have not been very successful. I am not sure if I mixed it to the wrong consistency, or if it is now too old to cure properly. It doesn't look any different, but instead of rock hard cement I seem to get something crumbly.

I cleaned it all up and stuck the thermistor back in with RTV silicone. I am sure it is not as conductive as Cerastil, but over such a short distance (between the thermistor and the wall of the hole it is in) I am hoping it will not have much effect.

I made the hole for it a bit deeper and opened out the top so it was big enough to accommodate the PTFE sleeving as well. That should keep it from touching the metal. It is surprisingly difficult to glue something into a small hole with a viscous glue. It is hard to get the glue to go down the hole without leaving an air pocket. A better idea might be to drill out a small screw, all the way through, fill it with glue from both sides. Then when it has set simply screw it into a tapped hole in the heater block.

I am waiting 24 hours for the silicone to cure now, so back to work tomorrow and less blog posts.

# Hot metal and serendipity

Tuesday, 5th January 2010 by Nophead

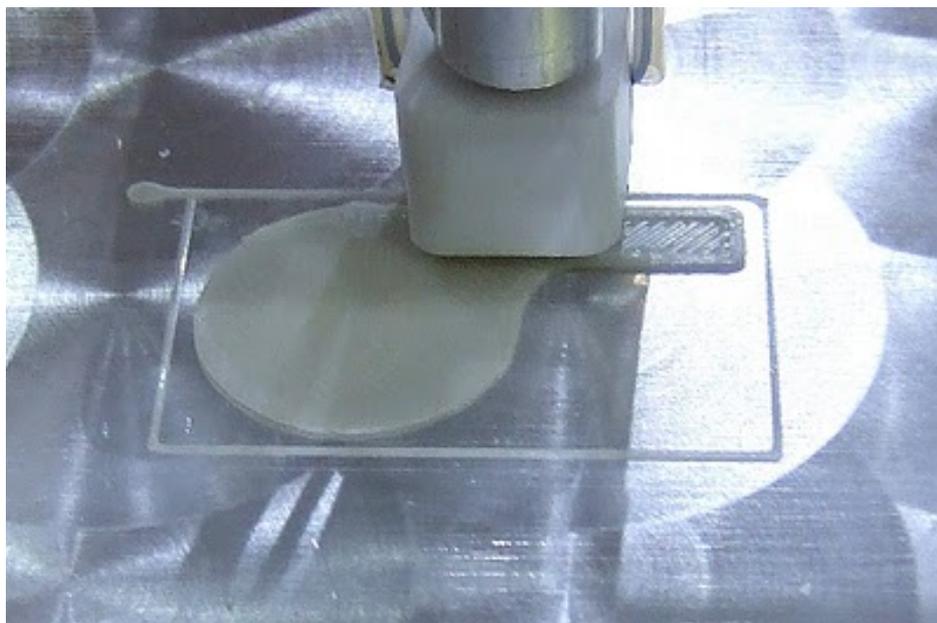
I couldn't get to work today because we had seven inches of snow during the night and a couple more today, so I had an extra day of RepRapping.

So my extruder is back working after re-fixing the thermistor with some RTV silicone. I get a degree or two more temperature swing with silicone compared to Cerastil, so not ideal, but it is workable. I think the plastic has such a high specific heat capacity and thermal resistance that it probably averages out the temperature swings anyway.

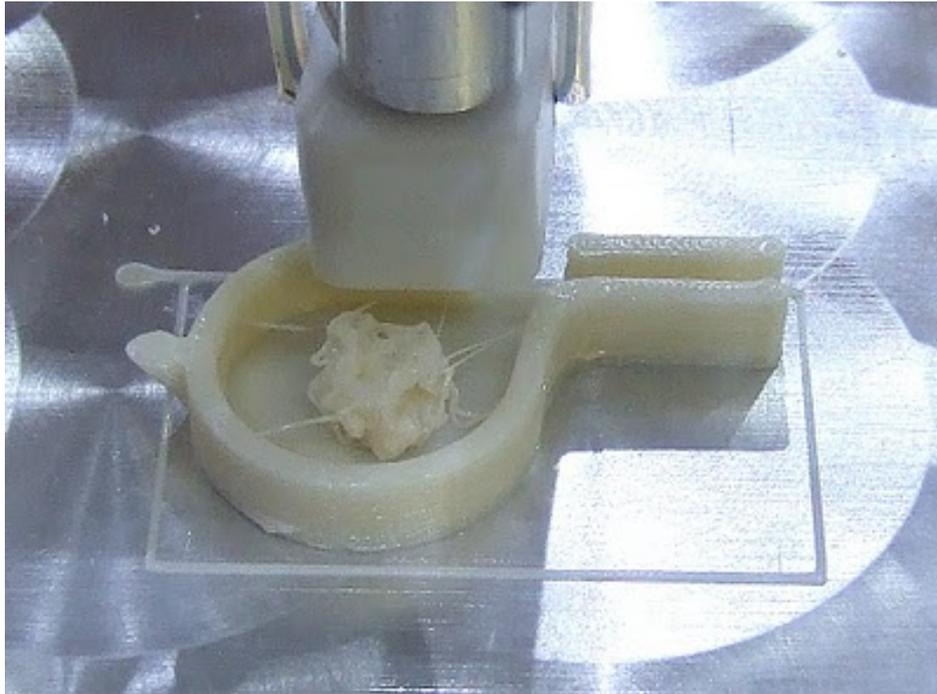
I switched to ABS to make a change from PLA as I am now able to use my 5kg spool of oval ABS that has always been two wide for my previous extruders. The bore of this one is 3.6mm, which is actually a bit on the big side for 3mm filament. I think about 3.3mm would be the best compromise.

My first experiment was to see if I could extrude directly onto my heated aluminium bed. My initial attempts failed to stick, even at 110°C, but I found that I could lay down a raft. I always cool the raft before applying the first layer of the object (I also drop the temperature of the first layer to 190°C), otherwise it welds too strongly to remove. When I cooled the raft it detached from the bed, presumably because it shrinks.

I reasoned if I could get the raft to stick then I should be able to get the object to stick. The difference is I do the first layer of the raft at 4mm/s and have the head lower than I would normally, so that the filament is squashed more. I tried making the first layer of the object at 4mm/s and a little lower than it should be. It almost worked so I upped the temperature to 120°C and tried again. This time I was able to make one of Zaggo's whistles.

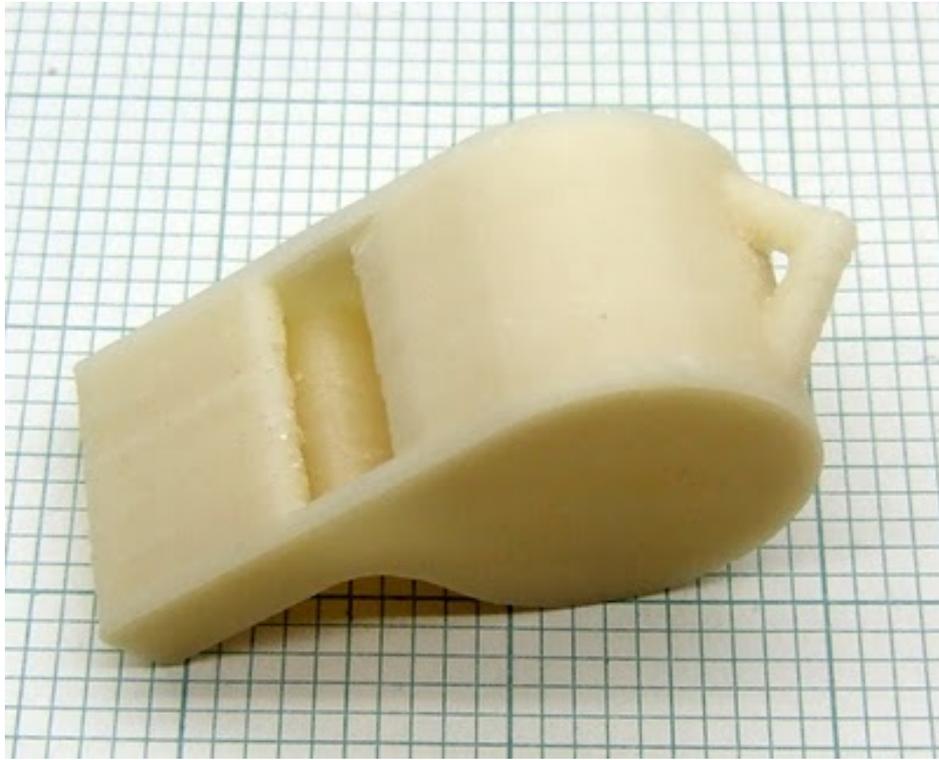


When it came to making the pea it got too hot and started moving around.



Normally I would use a fan on ABS to get small items to hold their shape, but obviously blowing cold air onto a hot base is going to waste a lot of power. The fix I have in mind is to blow a very small jet of air at the same temperature as the base and aim it just below nozzle. Hopefully by keeping the jet small I can avoid the sort of power that hair dryers use. Adding the heated bed has increased the power consumption of my machine by about 50W, which has more than doubled it.

When I cooled the finished object and the bed to 40°C, by running the fan, the object simply lifted off. At 120°C the ABS is like a soft rubber or gel. It clings to the aluminium, but will peel off with very little force. When it cools it becomes completely detached.

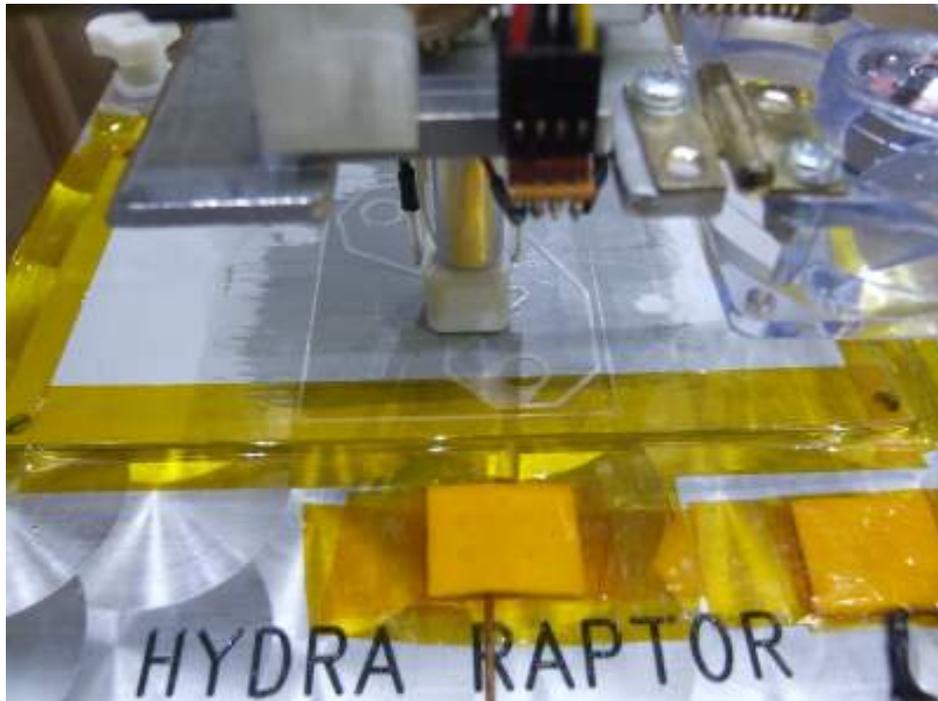


The bottom of the object is smooth and shiny and perfectly flat. I can actually see part of one of the swirls that are on my bed if I catch it right in the light. That means the plastic takes the texture of the base, so you could pattern and texture it in the same way as injection moulds.

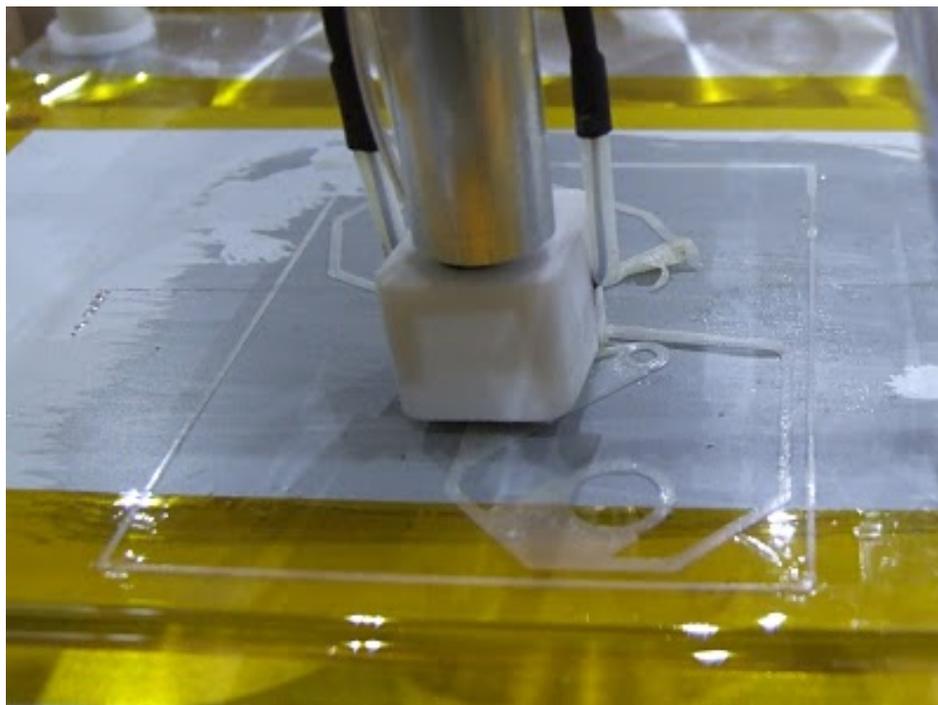
The next thing I tried was a Mendel vertex bracket as these are big enough to warp. It managed the outline, but when it started doing the outlines of the holes the filament failed to stick so I aborted that build.

The obvious way to get more grip is to use a sheet of acrylic as many people report that works well. I have a couple of problem with that though. Acrylic is a good insulator so the temperature control becomes more difficult. It tends to warp unless it is held down at the edges. I don't have any bolts long enough to mount it on my bed with the frame on top. I ordered some 2BA studding last year, but all the post from just before Christmas has gone missing.

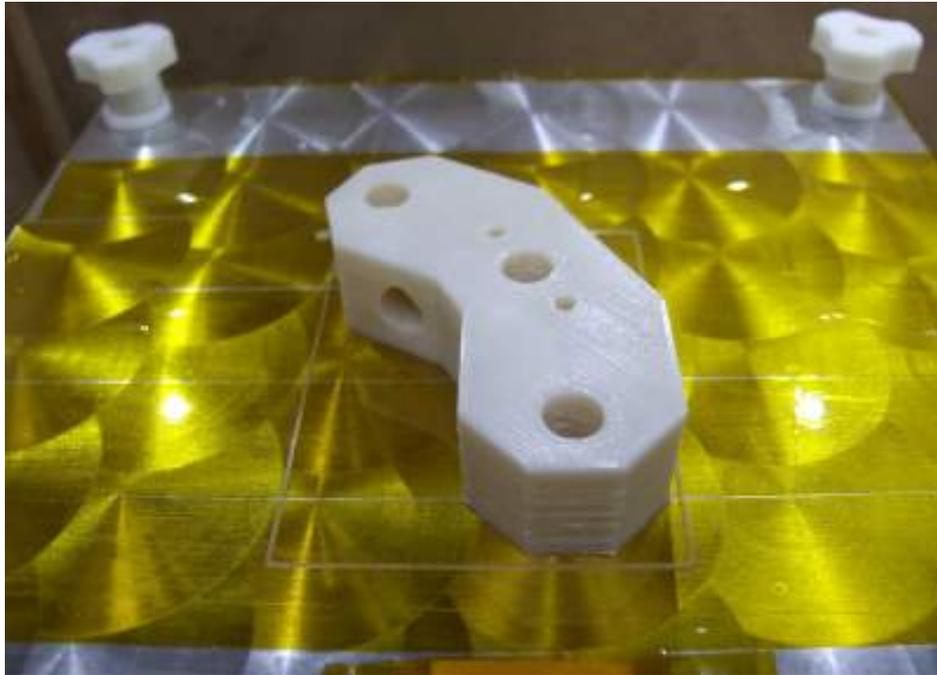
I looked around for a piece of metal with some texture and found some aluminium with a satin finish painted with metal primer, from a very old experiment. It looked promising to start with: -



But it soon snagged and started ripping it up again: -



However, as you can see, I held the plate down with Kapton tape and by accident part of the object was extruded onto the tape. It stuck well to the Kapton but was peel-able. This looked extremely promising. Kapton on top of aluminium could be the perfect bed material for ABS. It looks like it will be reusable many times, as masking tape is for PLA.



The bracket stayed perfectly flat during the build. I cooled it with the fan to 40°C. It was quite difficult to remove. In the end I put a penknife under one edge and tapped it with a hammer. It came off cleanly and with a perfectly flat base with a glassy appearance.



The only blemishes are the gaps in the tape, what looks like an air bubble in the tape, and the dent from my penknife.



The base is a slightly golden colour and that extends up for the first few layers so I think the bed was a bit too hot. I had it at 120°C and the first layer at 4mm/s, so I will have to back track a bit and see if I can get away with a lower temperature and faster first layer, but this is looking very good. No warping, no raft, a cheap reusable bed material and a mirror finish.

# Golden wonder

Sunday, 10th January 2010 by Nophead

My first attempt at extruding ABS onto hot Kapton had "all the stops pulled out" to make it stick, i.e. 120°C bed, nozzle height 0.1mm too low, very slow outline and infill on the first layer (4mm/s). The adhesion was very good so I decided to back off a bit. It is not a good idea to change more than one thing at a time but I did anyway. I got rid of the -0.1mm Z offset and sped up the first layer infill to 32mm/s, leaving the outline at 4mm/s. I also dropped the bed temperature to 80°C. That was too low, the corners lifted about 1mm during the build, but I think the part will still be usable.



The base is still glossy but you can see and feel some valleys between the extrusion "lanes". The next test was a binary chop with the bed at 100°C.



This is perfectly flat, even when off the bed for a day, but the extrusion lanes are still noticeable. The next test was at 110°C.



The extrusion lanes are gone in most places but a few are just visible. The first one that I did at 120°C has no extrusion lanes on it all, just some very slight graining from the Kapton tape that you can also see on the picture above. The tape lines and grain go from bottom right to top left. The extrusion infill slopes bottom left to top right and is only visible on the right hand side of the object. I think perhaps Z has to be a bit lower to get rid of them completely, but it is only important if you want to make something aesthetic, like an instrument panel, for example.

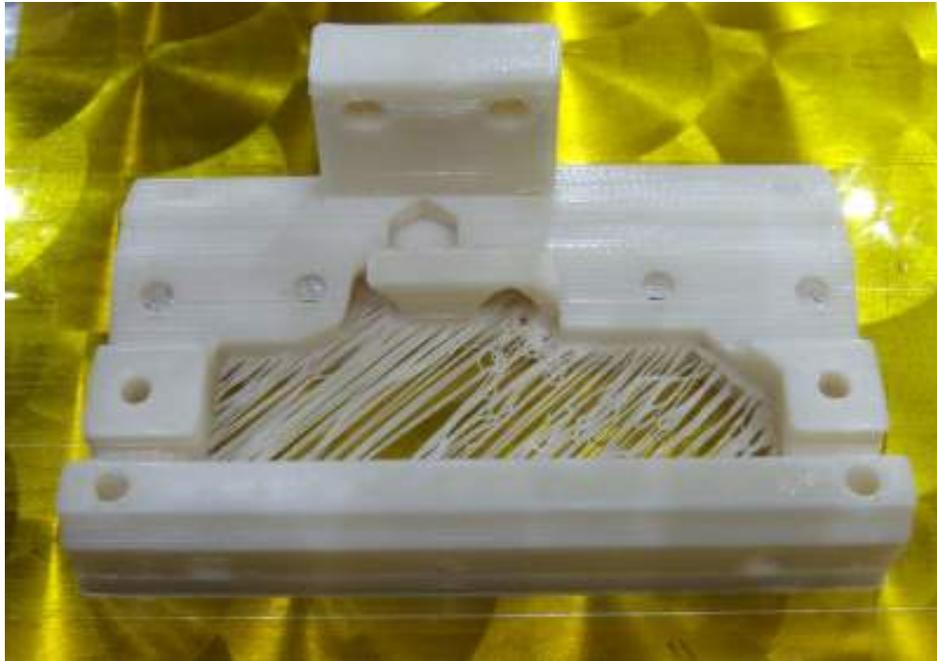
Of course there are the tape join marks. I used unbranded polyimide as it seems to be about half the price of branded Kapton. I got it from here, which is very cheap and free shipping if you don't mind waiting a while. You can get polyimide tape up to 250mm wide, but it is always on a 33m roll, so it gets very expensive. I have ordered a 150mm roll to cover the working area of HydraRaptor's build table. It was £53.71 from here, so very expensive, but a small price to pay for perfection! I don't know when it will arrive as post is a nightmare at the moment. I am still waiting for things from the 17th of December. Parcels are not being delivered because of the snow, so you have to go and collect them, but several letters and packets seem to have disappeared.

Here are all the tests side by side, notice the colour change with temperature, it is a bit exaggerated on the photo : -



I now have a full set of Mendel vertexes including two that I made in PLA that warped slightly (on a

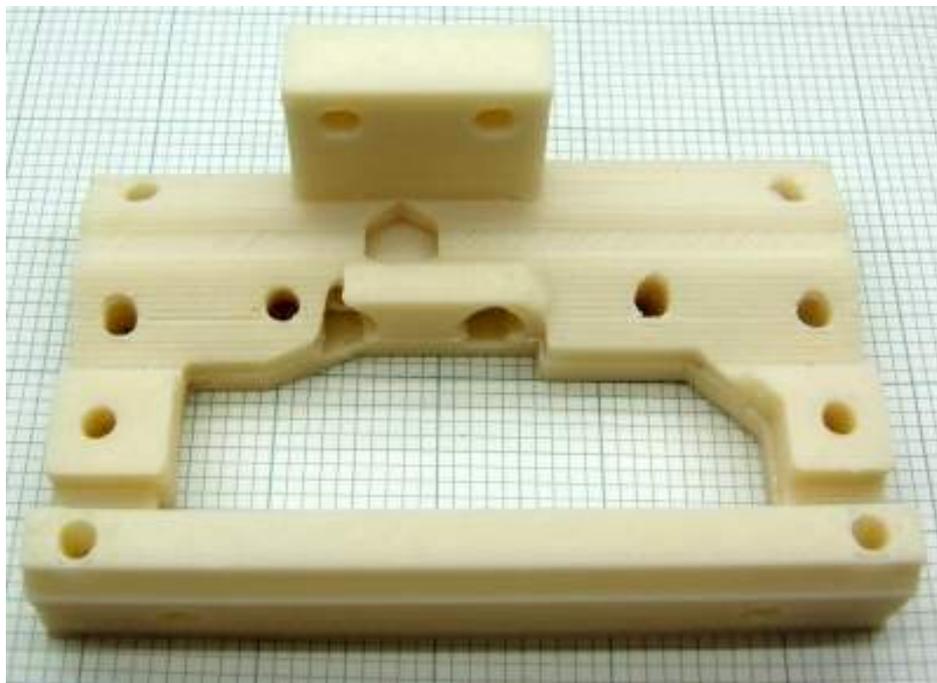
cold bed). I moved onto something more ambitious on the warping front: the Mendel x-carriage-lower\_1off part. I don't think this is printable in ABS without a heated platform, or air stream, unless you use the apron method developed by Forrest Higgs. For this test I started the bed at 120°C and dropped it to 100°C after the first layer. The logic being that 100°C seems to be enough to prevent warping, but 120°C is needed to get a perfectly smooth finish. It takes a few layers before the temperature has dropped to 100°C as I don't wait for the plate to cool down.



Unfortunately the ancient version of Skeinforge that I use gets one layer wrong on this part. The layer has the central hole missing. The filament didn't span the void very well as it is a very big void, I have no fan running and there is a lot of heat rising from the bed. That caused some filament to stick up and collide with the head. It spun round 90° unscrewing it 1/4 of a turn. Amazingly it did not leak but the nozzle hole must be slightly off centre with respect to the barrel thread, so I got an offset in X and Y above the layer that went wrong. Still, the objective was to test warping and it came out totally flat.



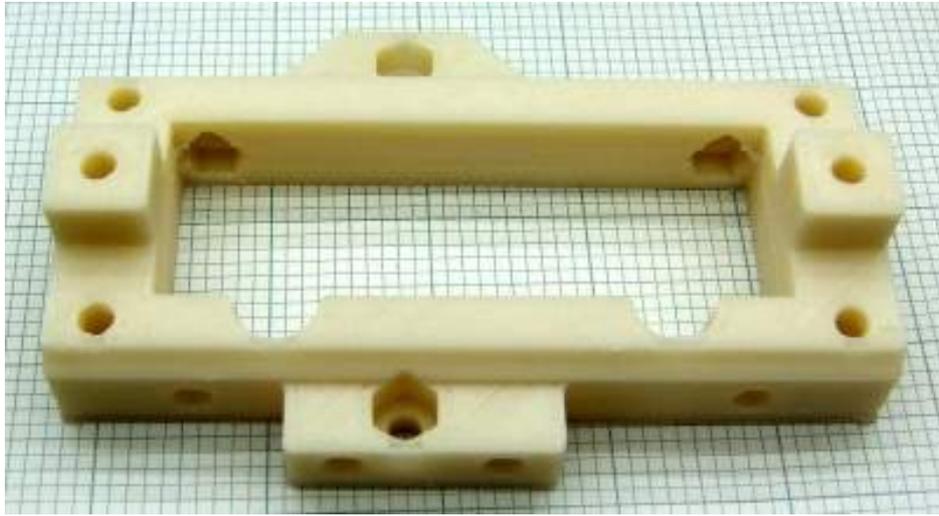
The corners have a dimple that looks like an air bubble, but must be something to do with them trying to lift I think. Apart from these the base is as flat as glass and had it not been for the Skeinforge bug it would have been usable straight off the bed. I cut the membrane out with a knife and drilled through the blinded holes before taking these pictures.



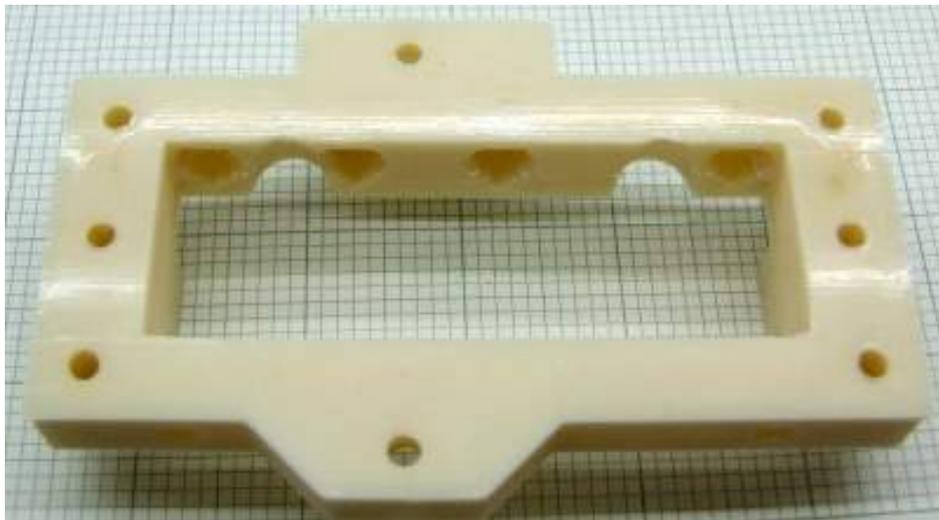
I tried the x-carriage-upper\_1off starting the bed at 120°C for the first layer and dropping to 90°C. Again Skeinforge got it wrong, not surprising as the topology is very similar. This time I also dropped the filament temperature to 220°C, so it spanned better and the head did not get spun. A longer snout on the nozzle might be a good idea to avoid collisions with build defects.



Again here it is with the membrane removed.



The corners lifted very slightly but the rest of the base is completely flat. It doesn't rock on a flat surface like an object made on a cold bed would. In fact, the raised corners made it easier to remove from the bed.



So it looks like 100°C bed temperature is the minimum to prevent warping when using Kapton. 120°C for the first layer gives a better aesthetic finish, perhaps with a small negative z-offset. Having the object kept warm seems to allow a lower filament temperature without losing strength. I used to build at 240°C and use 0.5mm for stronger objects. I can now use 220°C and 0.4mm with no sign of de-lamination so far. The lower temperature is good because the ABS out-gasses less and so smells less.

I can't recommend Kapton on heated aluminium highly enough. It has transformed my experience building with ABS completely. I no longer need a raft, which saves a lot of plastic, time and labour to remove it. My objects can be completely flat, smooth and glossy. Together with using a geared stepper extruder drive to completely eliminate ooze it means I just print an object, remove it from the bed and it is ready to use. There is a slight meniscus of plastic around the base, which you might want to remove with a file or a knife.

It has several advantages over acrylic: -

- Acrylic is a good insulator, so even 3mm reduces the surface temperature by about 15°C, making it take longer to warm up and harder to control.
- It tends to warp as it has a similar glass transition temperature to ABS.
- It can be hard to remove the object as it can be permanently welded if you deposit the ABS hot enough.

The way ABS sticks to hot Kapton is different. The Kapton does not melt at all so you don't get a weld no matter how hot the ABS is. I don't know what sort of bond it makes, but it is always peelable.

While I have been writing this article a friend came up with a brilliant suggestion. Why not use non-adhesive Kapton film, clamp it on the table, possibly with a vacuum? When the build is finished just release it so it can be peeled off the object with ease. I realised that would enable a conveyor belt table to be made. People have suggested this would allow a machine to churn out parts unattended. E.g., stretch a band of Kapton over a heated plate and rotate it when the object is finished and has cooled. The object will then drop off the end.

I still have a couple of problems to solve with the heated bed. The heat spreads downwards and warms my X-Y table. It is not much, I haven't measured it but I would guess to mid 40's C. That is enough to expand the aluminium that the table is made from and open up a gap in the ways so that it has some play and starts rattling. I removed the foam-board to leave an air gap (the logic being that the movement of the table would generate some cooling airflow) and covered the top of the bed with aluminium foil to reflect the heat back. That helped, but not enough. I think I will need to blow cold air over the top of the table with a sheet of something like PTFE to cover the bottom of the heated bed.

The other issue is that having heat around the object rather than cold air blowing on it means that void spanning and overhangs don't work as well as they did. I think I need a jet of warmed air directed at the end of the nozzle to cool filament to freeze it quickly.

# Stepping up to the mark

Monday, 11th January 2010 by Nophead

My wife is a very measured person. As well as watching how much power we using she likes to count her footsteps with a pedometer to check if she is getting here daily quota of 10,000. I have bought her several pedometers but they generally come to an early demise due ti inadequate belt clips. The last one fell into the toilet! The first one I bought was the best, but the belt clip broke off.



I promised to RepRap a new clip a long time ago, but only got round to it today. Neither of us could remember what the old clip looked like so I designed a simple one from scratch. To my surprise it printed perfectly on the hot bed, I thought it might need some cooling. HydraRaptor will have automatically dropped to half speed because the layers are so small.



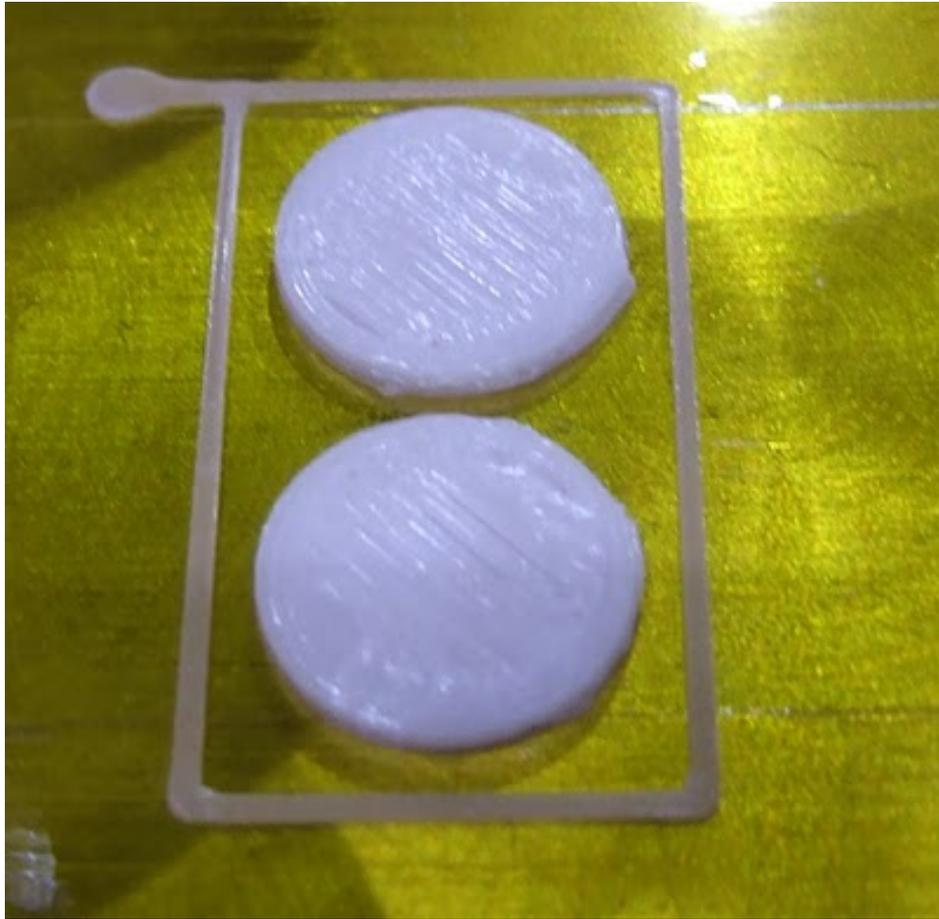
I cut off the remains of the old clip and filed it smooth. I then removed all traces of grease with some isopropanol and welded it on with some MEK pipe cement. A friend gave me it anticipating

that I might want to weld ABS someday. It will dissolve and weld ABS and PVC. I think the case is ABS, so it is ideal for the job. It needs 4 hours to cure, so I left it overnight.

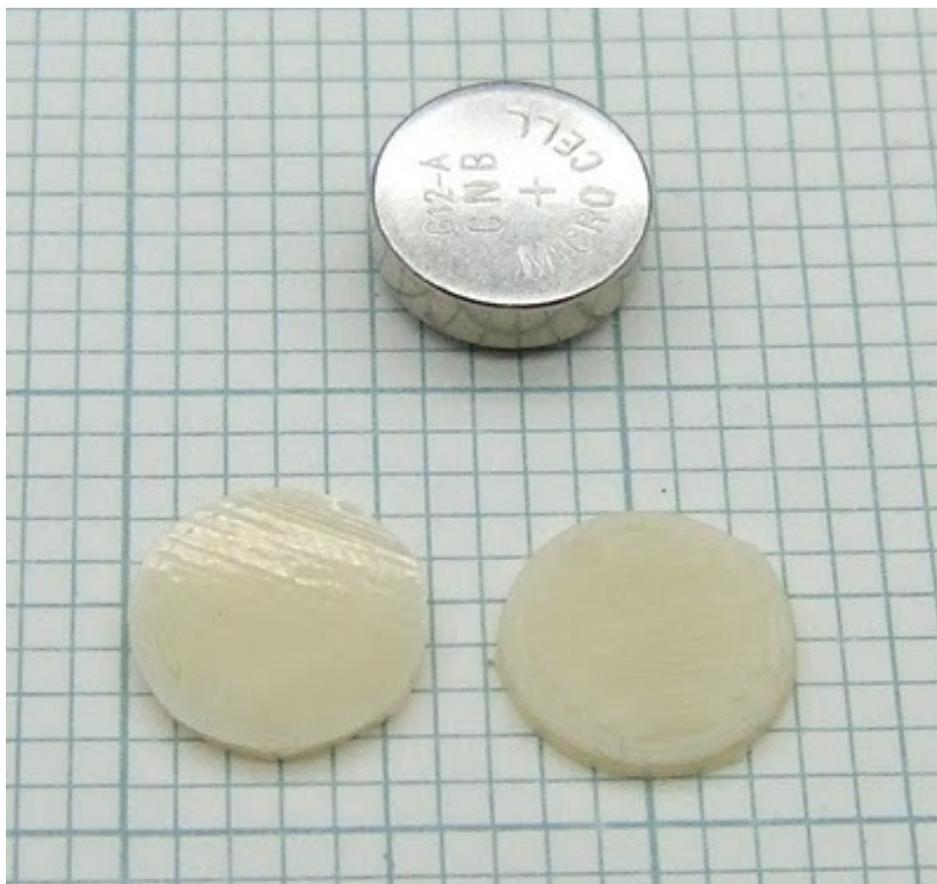
It seems to have done the job. I offered to make it in black but my wife wasn't bothered.



The next problem was that the batteries had gone flat in the years she has been waiting for me to fix it. Buying specific batteries is expensive but you can get a mixed selection of 40 for £1. The problem is though that we mainly use the biggest ones so have too many of the smaller ones. I had some that were the right diameter but too thin so I Reprapped some spacers.



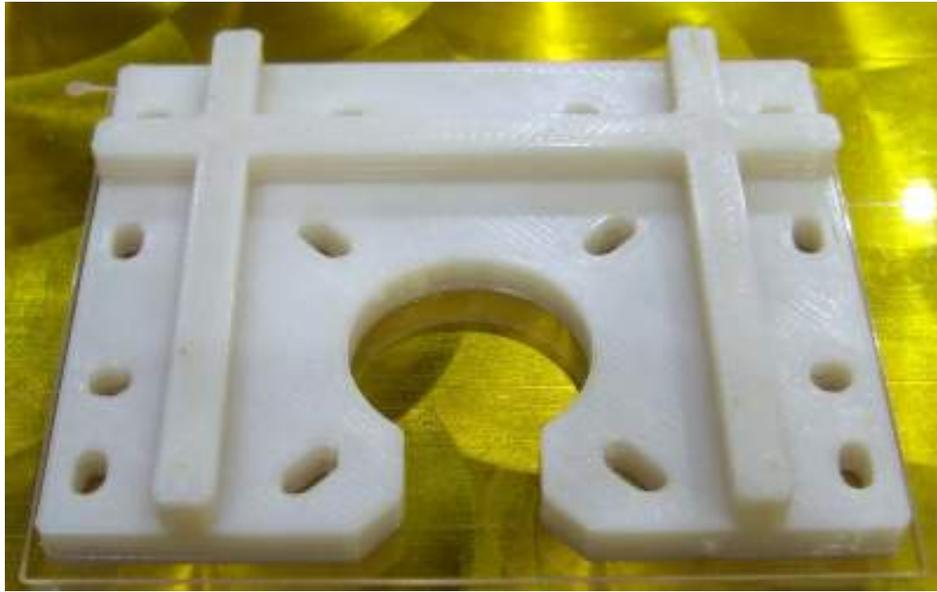
I can now make objects side by side one layer at a time with no strings between them. These are probably the smallest things I have made. They are about the size of tiddlywinks.



A bit tricky to keep in place while the battery cover is replaced but they did the job.



So I am back in the good books for a while. I managed to run off two of these as well. They take about 90 minutes each and are perfectly flat and string-less again.

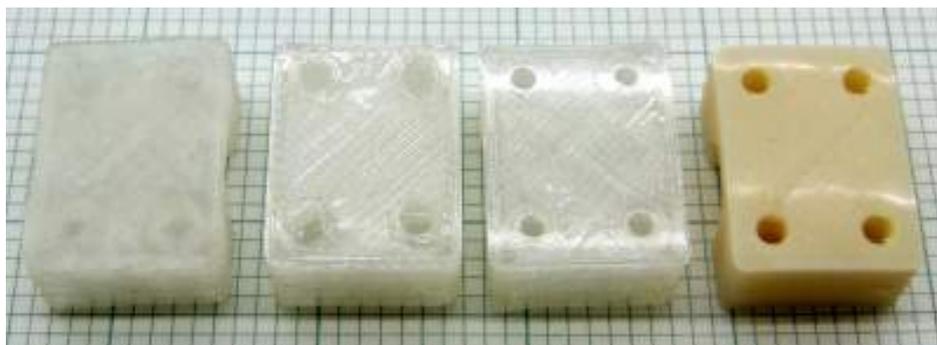


Just the odd lump on the surface at the start or end of an outline. I think that can be easily solved by always starting on an inner shell before doing the outer shell and then finishing the outer shell with a wipe towards the inner one.

# Will it stick?

Saturday, 23rd January 2010 by Nophead

ABS sticks very well to hot Kapton, so I wondered what else would stick to it. The first thing to try was PLA. This sticks pretty well to cold masking tape and doesn't warp much, but large objects do have some warping. I figured heating the bed to around 50°C would fix that. Rather than changing from Kapton to masking tape I decided to see if I could stick PLA to Kapton and get a shiny surface as well.



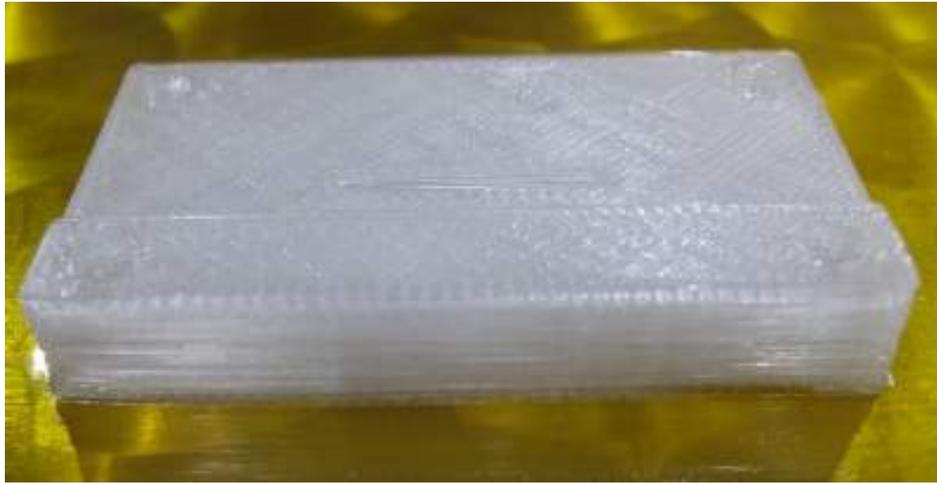
The first bracket was made on cold masking tape so the base has a matt finish.

The second one is on Kapton at 50°C for the first layer, dropping to 40°C after that. My logic was to have the bed just above the glass transition to make it stick and just below afterwards to stop it warping. As you can see one of the hole outlines did not stick properly. The PLA was extruded at 200°C for the first layer and 180°C for the rest.

For the third one the bed was at 55°C falling to 45°C. The outline stuck properly and the base is nice and shiny. The surface imperfections you can see are from gouges in the aluminium bed caused by a slight accident with a decimal point. It caused the nozzle to be rammed into the bed and then the X-Y movement ploughed furrows. These show up through the Kapton tape.

The last one is my first ABS test for comparison.

It was looking good, so I tried something bigger, a Mendel belt splitter jig: -



The left hand corner lifted and the object ended up more warped than it would have been made on cold masking tape.

I tried again with the bed at 55°C all the way through the build. My extruder started jamming so I increased the PLA temperature to 210°C for the first layer and 190°C for the rest, the values I had been previously using on cold tape.

This time it was successful and stayed stuck down: -



The base came out perfectly flat and more transparent: -



The extrusion lines of the three solid base layers are less visible and you can see through to the sparse infill. This is only 25% but the object feels incredibly strong. I get the feeling the hot bed makes things stronger.

There is a bit of a meniscus around the edge. This is mainly because I had a bodge of a -0.1mm offset in the first layer outline to get PLA outlines to stick to tape reliably. I removed the bodge and made this object: -



The base layers are very transparent here, even more so to the naked eye than the camera shows. There is something a little odd with some of the extrusion lanes above the bottom left hole.

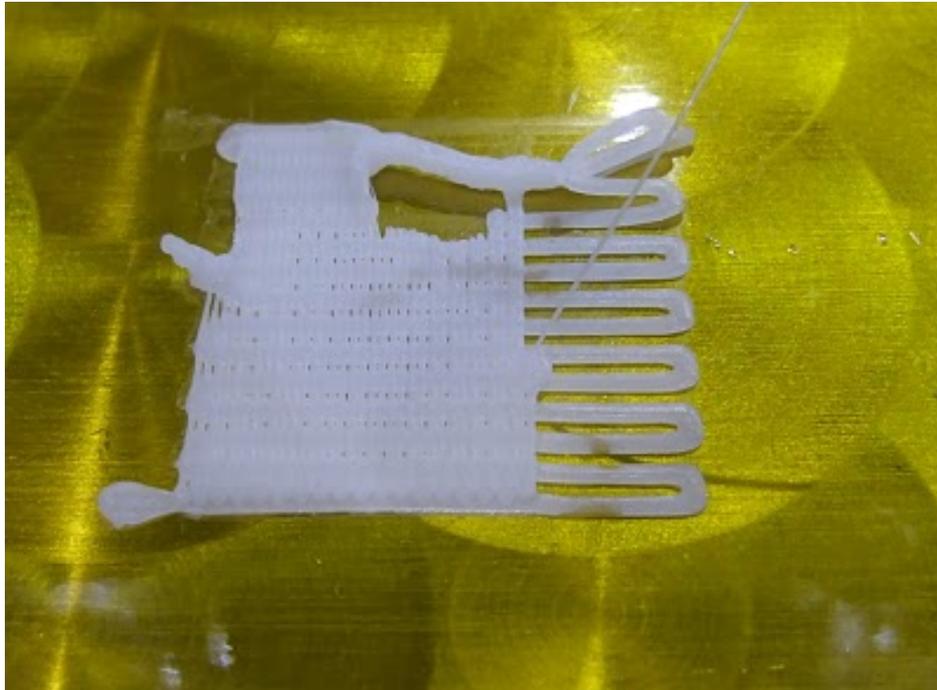
I think those discontinuities must be the plastic squirming a bit while extruded, which is usually a sign of not being stretched enough.

The top of the object has a small defect: -



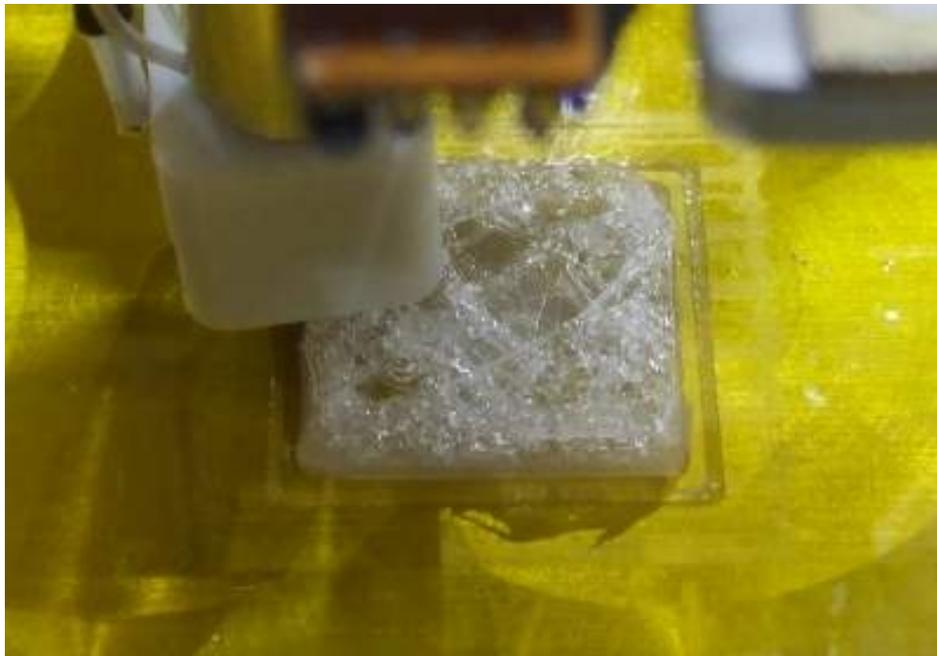
There is a small hole above and right a bit of the centre. I think this is because the plastic doesn't span gaps as well without a fan, so it fails to bridge the sparse infill properly. I wasn't watching so I didn't see exactly what went wrong.

The next plastic I tried was HDPE. Not surprisingly it doesn't stick very well to hot Kapton. With the bed at 130°C it stays molten but is quite rubber like. With the bed at 110°C it sets and turns white (because it crystallises I believe). I tried various combinations of these two temperatures but could not get it to stick reliably. I could lay down the first layer of a raft but then subsequent layers would rip it up as the adhesion is very low.

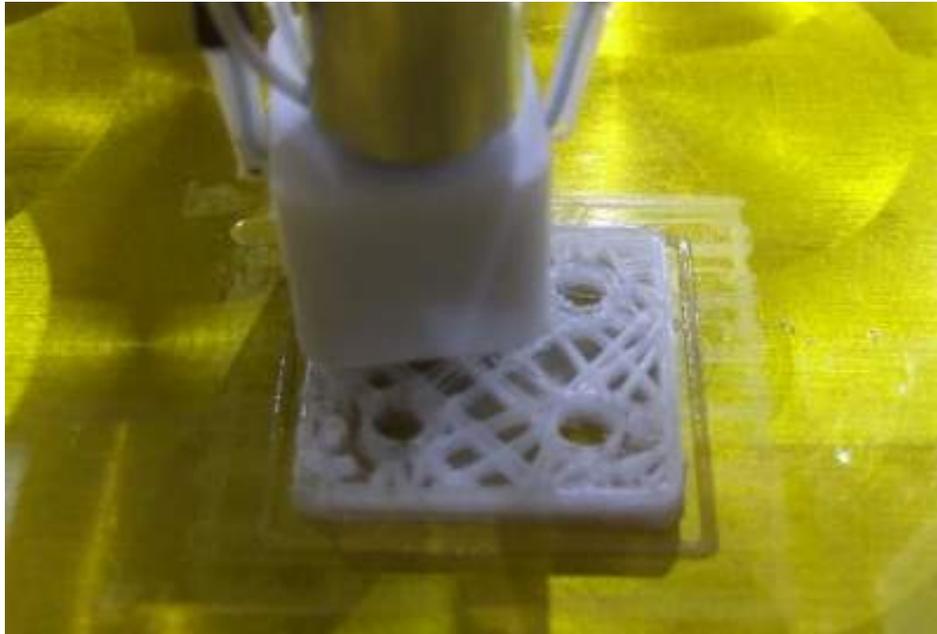


I think the way to do HDPE without a raft is to extrude it onto a thin sheet of HDPE, or maybe polythene, held down by a vacuum and heated to prevent warping. That will have to wait until I build a little vacuum table, hopefully this weekend.

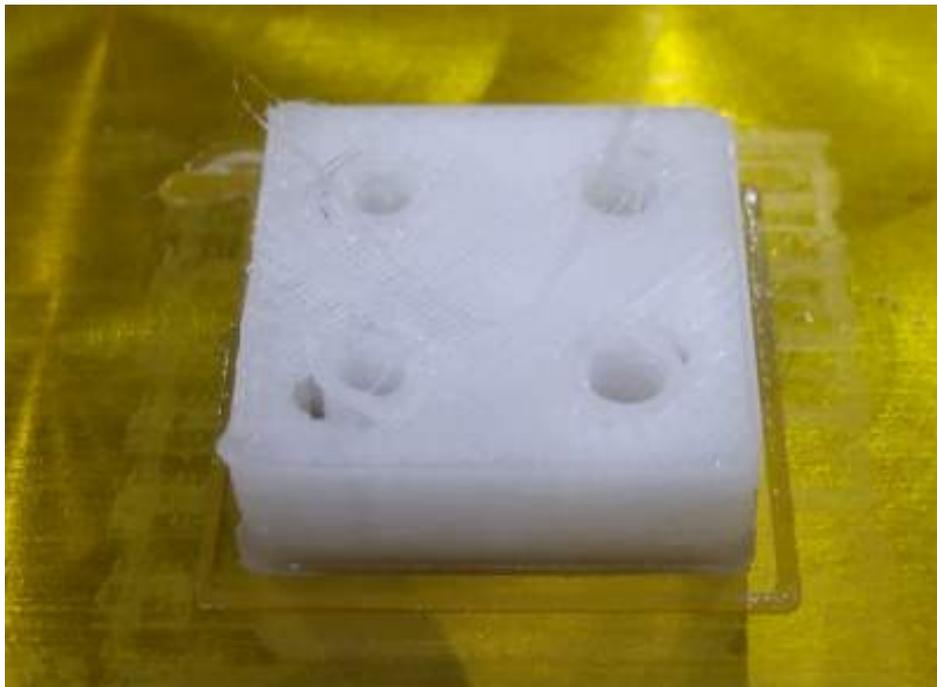
Last on the list was PCL. That sticks very well to Kapton heated to 40°C but it never sets and makes a soggy object.



Before the heated bed I used to build with a fan, and at only 40°C the bed has no trouble holding temperature, so I tried with the fan next.



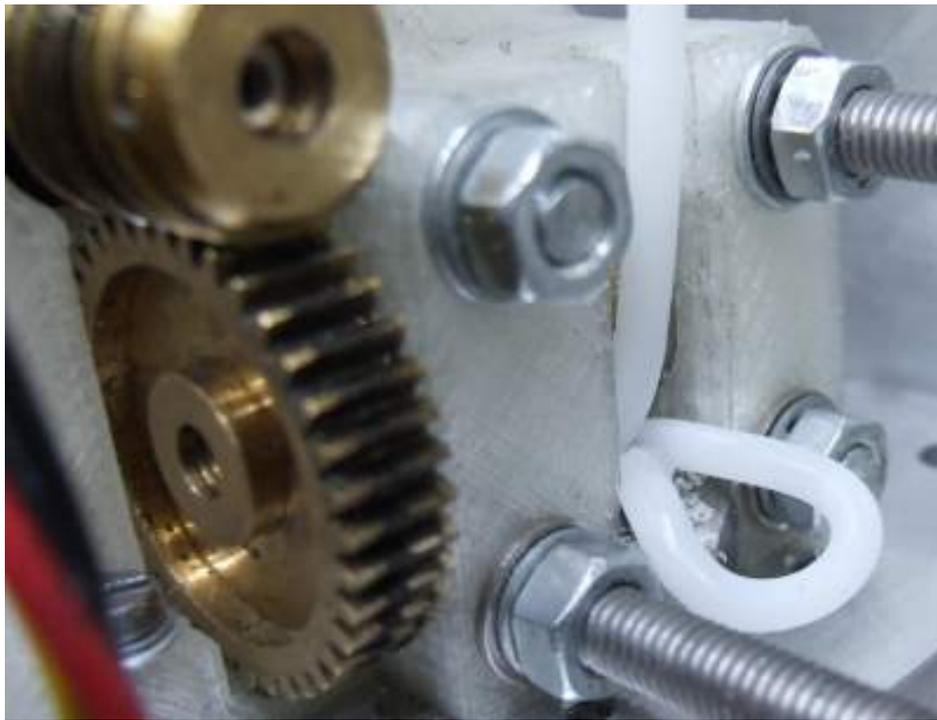
That worked OK and built a complete object: -



The infill did not stick very well to the outlines of the holes, especially on the downwind side. It probably needs a denser infill, and perhaps some overlap. 25% fill is not really appropriate for PCL as it very soft and flexible.



The bottom is smooth and shiny as expected and it took some effort to peel it off, so I expect large objects could be made. I couldn't experiment further though because the filament started buckling in my extruder.



I can't explain why it worked for a while and then stopped but I tried higher temperature and slower extrusion but could not get it reliable again. The pipe could probably be a few mm closer to the pulley but not much more because it would hit the pinch wheel.

I don't have a lot of use for PCL, other than using it up. Dropping it from the requirements for the extruder would allow me to use a smaller pulley. If you look at the table at the end of [this article](#), you can see that it is only PCL that struggles for grip with a worm pulley. I think I could drop to half

the diameter, which would just about bring the gear ratio into the range of a single pair of spur gears. I have a 4" Meccano gear that gives 7:1, so I might try that in my next extruder.

So hot Kapton works well for everything I have tried so far apart from HDPE.

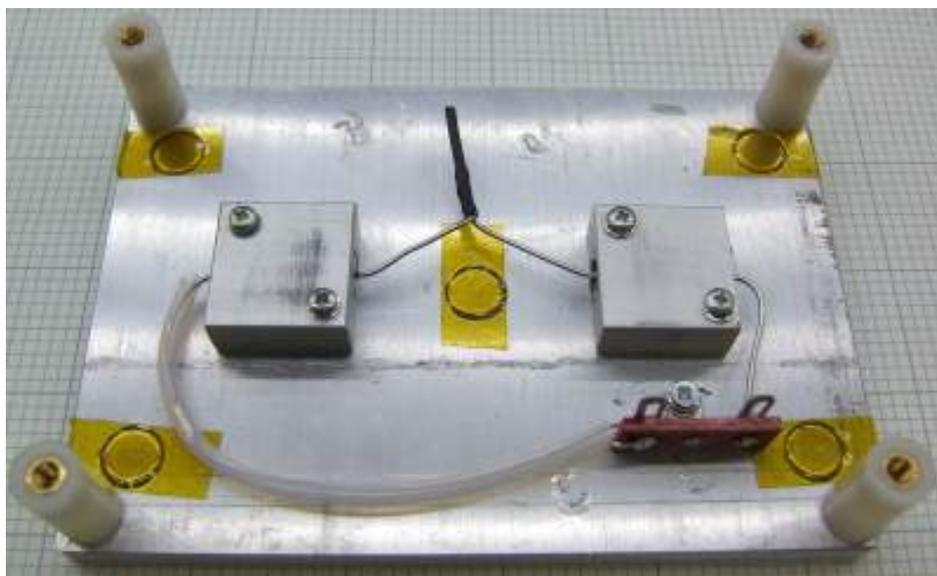
# Quick release bed

Sunday, 31st January 2010 by Nophead

I am in the process of making a heated vacuum table to hopefully allow automatic ejection of finished objects. In a conversation with Laszlo he mentioned he was planning to use a heated steel bed and use magnets placed around the object to hold down a sheet of Kapton. I turned the idea upside down. Why not stick Kapton tape to a sheet of steel and clamp it to a heated aluminium bed using magnets underneath?

I found a thin sheet of bright springy steel that was part of an electric toaster. My best guess is that it is one of the grades of stainless steel that is magnetic. It is only 0.3mm thick so it is relatively flexible, but it always springs flat. It came from a Kenwood toaster that gave good service until our cleaner suggested to my wife that she should turn it upside down to get rid of some persistent crumbs. The next time it was used it burst into flames because a crumb got wedged between the element and the steel plate and burnt through the nichrome.

I made a tiny heated table from an off-cut of 6mm aluminium. It is only 105mm x 73mm, which is smaller than a MakerBot CupCake bed but I think it is just big enough to make all the Mendel parts.



I have run out of AL clad resistors so I made my own from vitreous enamel ones embedded in aluminium blocks with tin foil. I used two 6.8 resistors in series driven from ~ 26V AC. That gives about 50W and a similar warm up time to my larger bed driven with 200W.

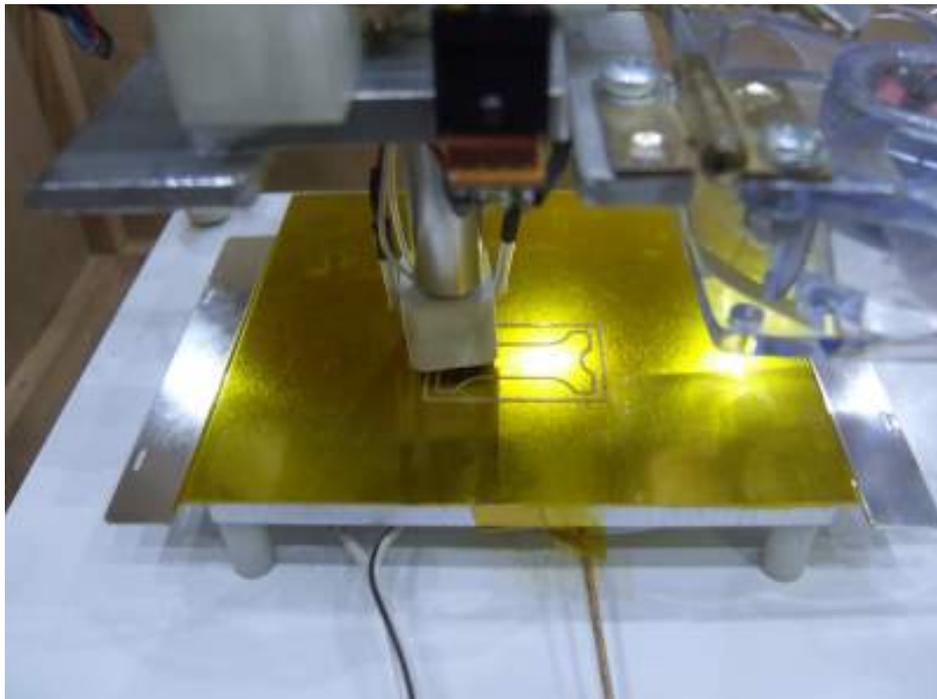
I milled flat bottomed holes to within about 1mm of the surface and embedded five neodymium magnets which are held in with Kapton tape.

I used M3 threaded nylon stand-offs as insulated table legs and mounted it onto my XY-table

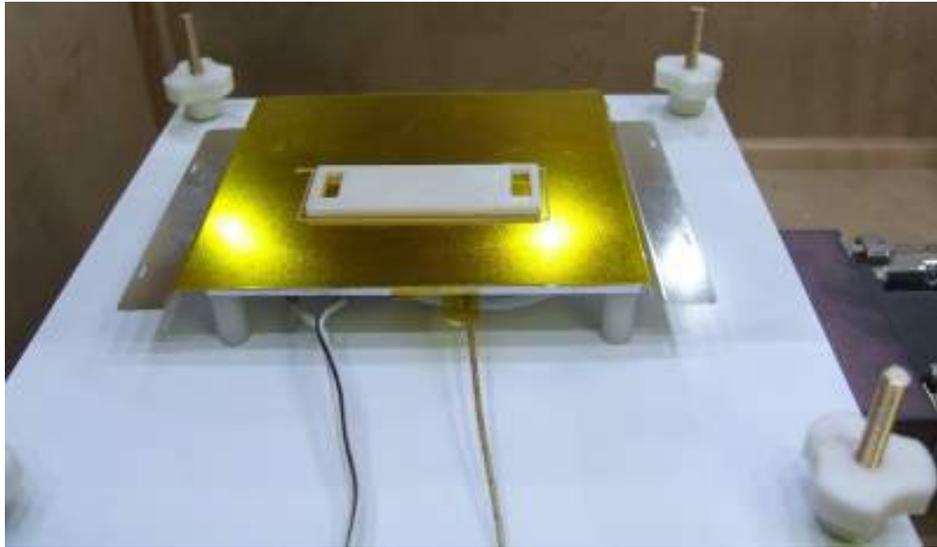
using a sheet of 4mm aluminium / plastic laminate called Dibond. It is very nice material to work with.



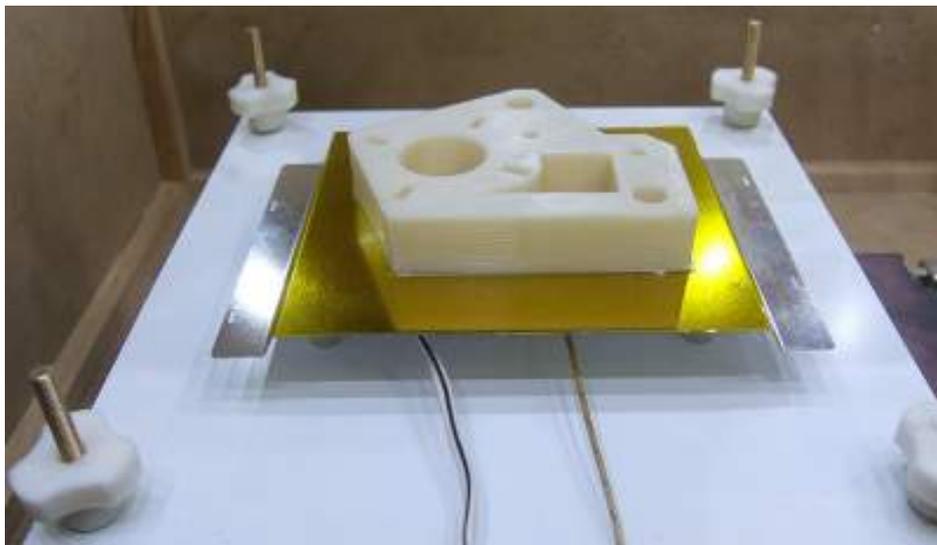
The steel plate covered in Kapton tape then sticks to the top of the table. I heated it to 100°C and tried making some ABS objects.



This worked well and the objects were easy to remove by bending the plate and peeling them.



The magnets are strong enough to hold down even big objects. The only problem I had was that the nozzle snagged on the first layer of this object and managed to slide the steel plate, causing the first layer to be offset.



Contrary to popular belief, FFF does require significant force and benefits from a stiff extruder mounting.

A couple of pins in the corners to act as dowels would solve the sliding problem.

Here is a video showing how easy it is to remove the objects: -

It is still a manual process though, so I will pursue the vacuum table idea to attempt to make a bed that can eject the object itself.

# Suck it and see

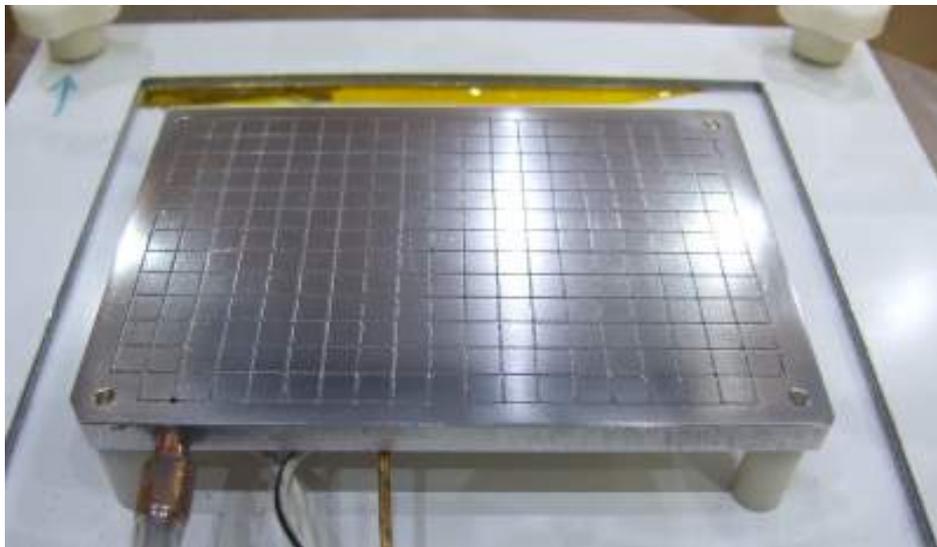
Thursday, 11th February 2010 by Nophead

The magnetic steel and polyimide tape bed works very well for manual operation but I am pursuing the vacuum bed idea for fully automated production. I went through a few designs in my head before actually making anything.

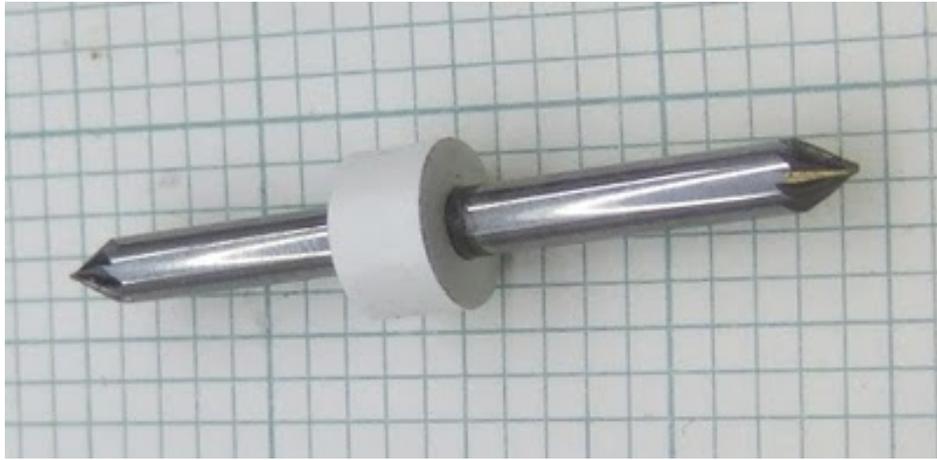
The first idea was to drill an array of holes through an aluminium plate and connect them on the back by milling a network of channels. I would close the top of the channels with some Kapton tape. The problem with that idea was there was then nowhere to mount the heating resistors unless it was on top of the Kapton sealing tape, which didn't seem ideal. My solution to that was to mill a channel into the edge of the plate and wind a coil of nichrome all the way round it. That was my plan until I realised there would then be nowhere to attach the vacuum hose.

A solution might be to use a Kapton or silicone stick-on heater and use it to seal the channels in the underside.

What I actually did was to mill a grid of very fine channels into the top surface allowing me to attach the vacuum hose to the side edge and drill a small hole down to meet it, leaving the bottom free for the resistors and thermocouple.



The channels are about 0.5mm wide and 0.5mm deep on a 5mm grid. I milled them with a 0.3mm conical bit that I bought for milling PCBs.



I used a feed rate of 2mm/s and 0.1mm cut depth per pass. My MiniCraft drill runs at about 20,000 rpm. The results were not very good. I have only ever milled plastic before with HydraRaptor. It struggled cutting aluminium such that the shaft of the drill was being displaced in the direction of the bed travel. It raised a burr about as high as the channel is deep. My friendly local milling consultant told me afterwards that aluminium does not like lots of flutes. He recommended a D-shaped cutter with a single cutting edge and a higher spindle speed.

I sanded the surface flat with 240, 600, 800, 1200 and 1800 grade wet-and-dry sandpaper and then polished it with metal polish. I did this to get as good a seal as possible with whatever was placed on top.

I attached some polythene pipe using an M5 copper welding nozzle screwed into a tapped hole in the side of the plate. I use a tapered tap so that the thread would bind to form a seal. I used Fernox LS-X jointing compound to make sure it was airtight. I think it is silicone, so should handle the temperature.

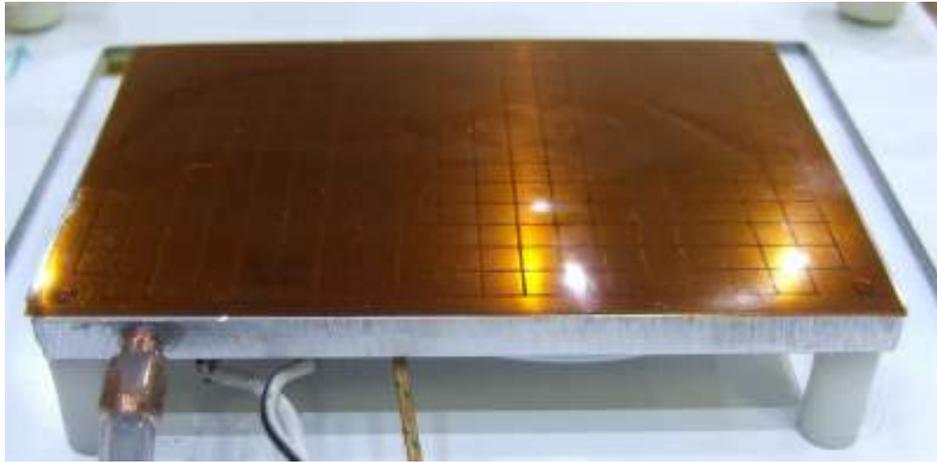
I was hoping to get a perfectly air tight seal and be able to use a static vacuum generated by a syringe. It doesn't seal fully though. I believe normal vacuum tables use rubber o-rings set into a groove to form a seal. I reasoned that would not work in this case because, whereas sheets of stock for milling are stiff enough to remain flat and squash the rubber, thin films would just bend upwards. My idea was that the thin film would be sucked into the channels and be compliant enough to seal it. I think it fails because the edges of the channels are too rough due to my poor milling.

I first attached a small vacuum pump that I made for my jukebox. It is just an aquarium pump with a pipe attached to the air inlet and the case is sealed with rubber glue.



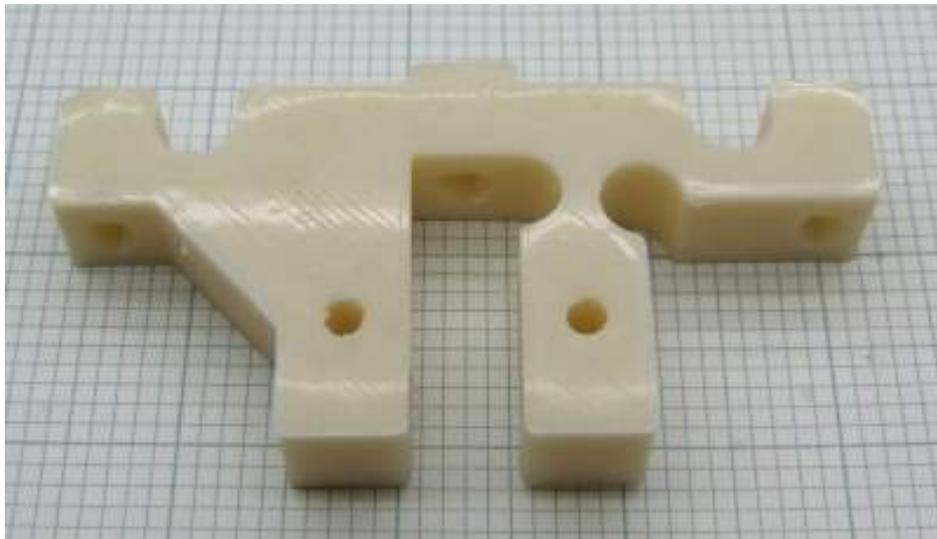
It is not a very strong vacuum, but it is enough to pick up a CD with a suction cup made from the end of a child's rubber dart. I plan to use it for SMT pick and place soon. I measured it at 960 millibars, which is also the extreme low reading on our barometer. I knew that the vacuum it created was less than the atmospheric variation because I started off with an absolute pressure transducer on my jukebox to detect if a disk had been picked up. I had to change the trip point about twice a year because one setting would not work for both extreme high and low weather conditions. In the end I added a second sensor to make it differential.

I placed a piece of 0.075mm polyimide film on top. This is about twice as thick as the tape I use.

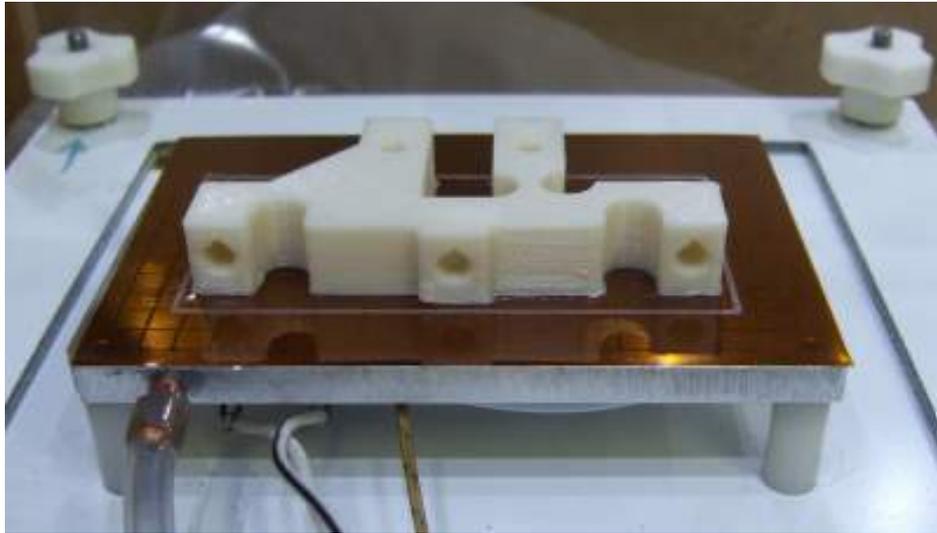


The video below shows the effect of the vacuum. It pulls flat and has some resistance to sliding but is not a very strong grip.

I built a Mendel part at 100°C for my first test. The film stayed flat during the build but a few corners lifted. When the part cooled it broke the vacuum and wrinkled the sheet. It was past the point where it had hardened so the base was perfectly flat apart from where the top corners had lifted slightly during the build.



I measured the temperature of the surface and found that it was 10°C lower than that measured underneath by the thermocouple. I raised the set point to 110°C and made another part. This time only one corner lifted (left side of the boss in the middle) .



Here is a speeded up video of the film releasing as the bed is cooled down to 40°C by a fan.

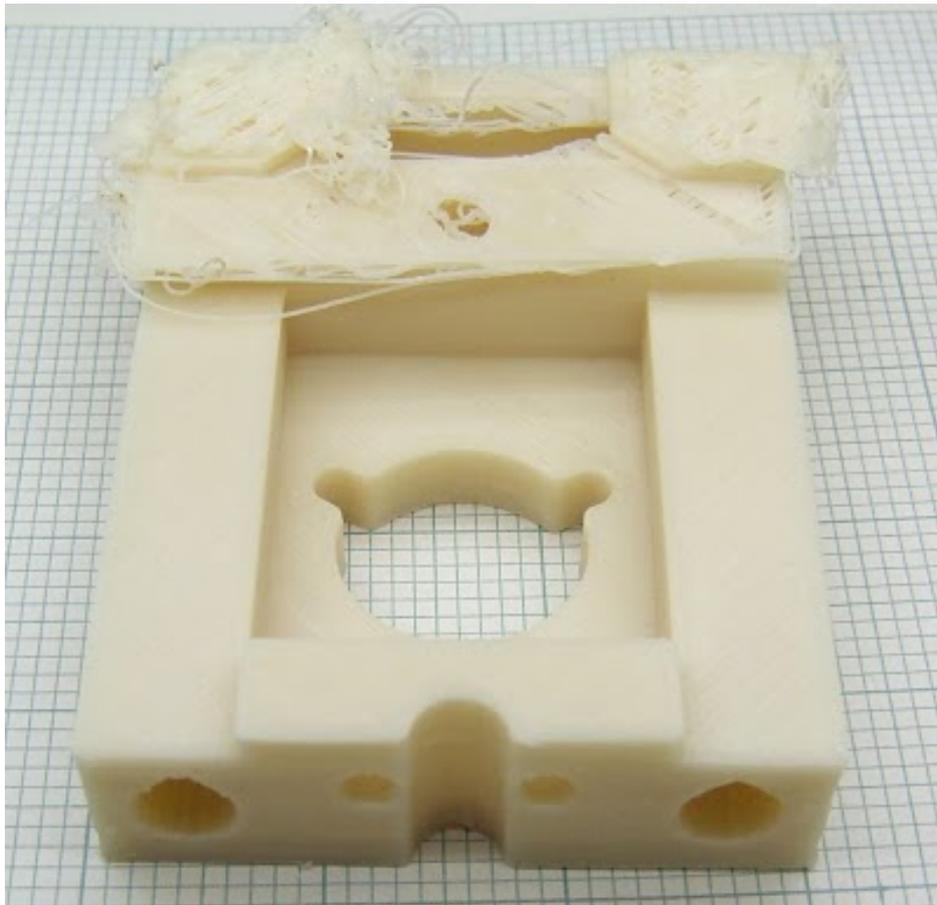
And here is me simulating removing the object by sliding the film. Ignore the 16 annotation, I am not that slow!

The next thing I tried was a really big part of Mendel. I didn't trust my weedy aquarium pump to hold it down so I used a 1/4 HP 180W 3 cubic feet per minute pump rated to go down to 0.1 millibars. I bought it for £150 over two years ago to make a vacuum bed for milling but never got round to it, so it has been sitting on a shelf, like a lot of other parts and materials I have bought for experiments but not had time to use.



When connected directly to the vacuum gauge with a length of plastic hose it goes down to about 30 mb. I think I would need better quality fittings and pipe to get down to 0.1 mb. When connected to the vac table it gives 40 mb, so although it does leak, it still gets most of the available downforce from atmospheric pressure, i.e. ~15 lbs / square inch.

The part I made ended in disaster because the vacuum broke during the build. I think it was mainly because the object was not quite centred on the table so its outside perimeter was on top of the last vacuum channels. Before it failed some corners had lifted a little, early in the build, so it looked like the ABS does not stick to film as well as it does to tape.

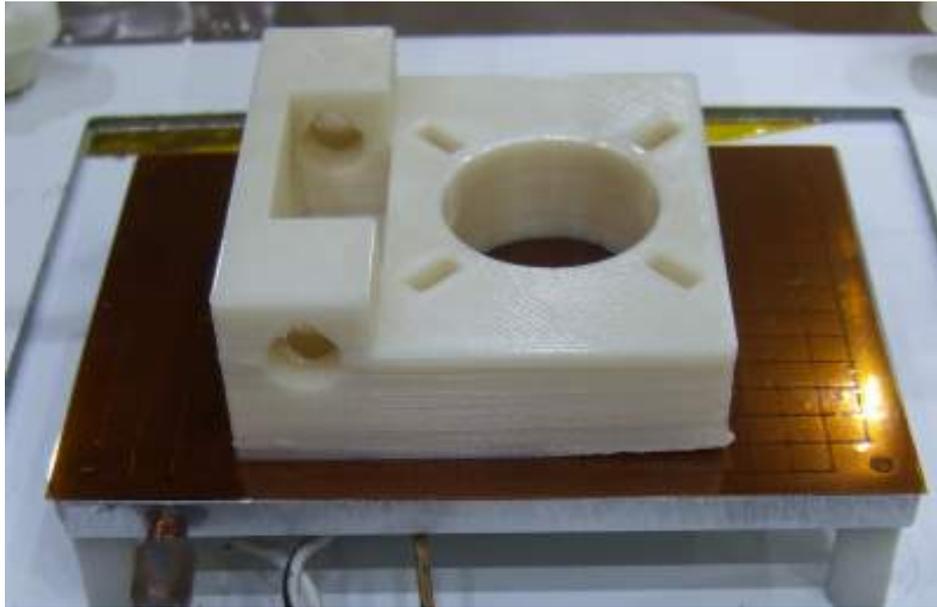


I centred the table and made a slightly smaller piece. Actually this was the same depth as the last piece, so the perimeter falls about half way between the last two channels. Ideally I think you don't want to be that close to the edge.

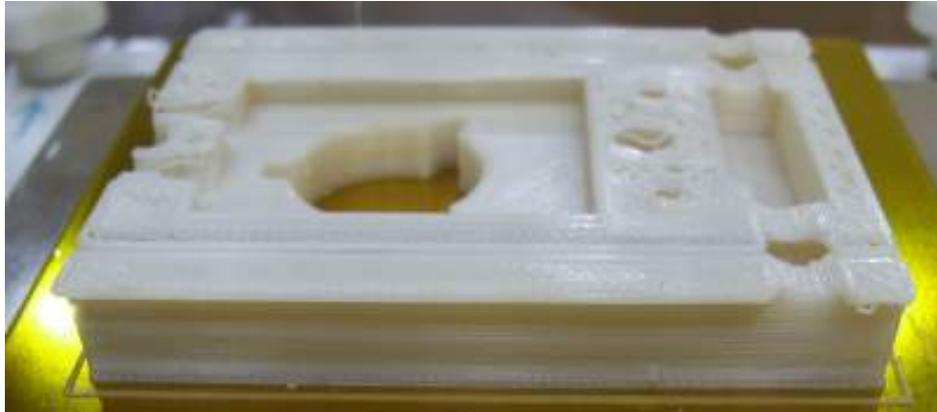
I raised the temperature to 120°C, so the top of the film was probably ~110°C.

The film stayed vacuumed down during the build but still broke the vacuum and wrinkled during the cool down period. That means that even with close to the maximum vacuum it cannot hold the contraction force. Not a big surprise as I realised a long time ago the warping can generate a lot more than 15lbs / square inch of pull. The only reason I thought this might work is because the plastic does not warp while it is kept hot and indeed the vacuum holds during the build. The problem is that the object does not stick to the film well enough. One corner peeled early on and lifted further as the build progressed. The rest of the base is flat though, so the part is easily good

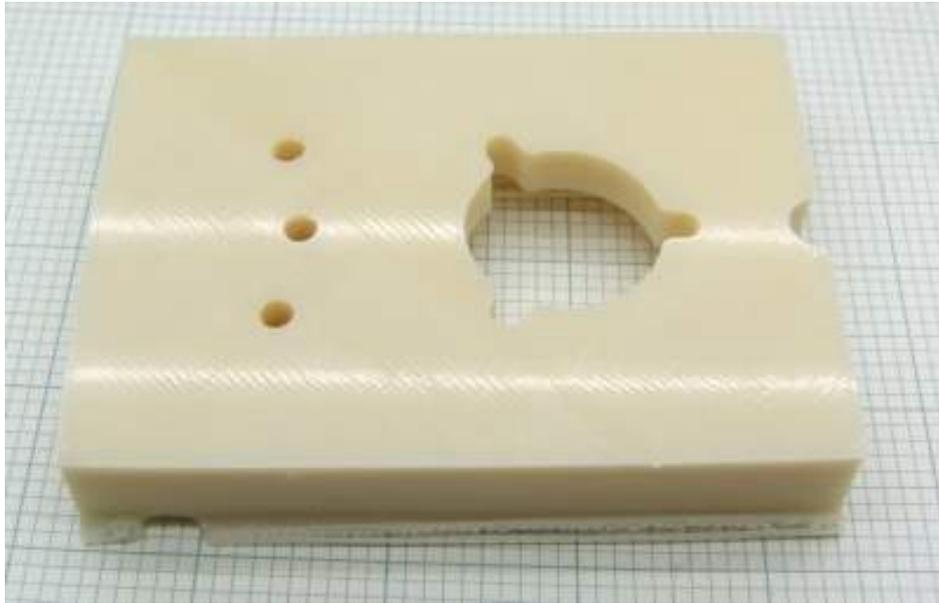
enough to use. The higher temperature and vacuum meant that the grid lines are just visible on the object base if you get the light right.



So just to make sure I can make an object this size on tape without warping I made the larger part again on my magnetic bed. That failed because the bed slipped part way through. I knew that was a likelihood and that I need to add a couple of dowel pins in the corners, but I didn't want to do that while I was experimenting with vacuums. I gambled on it not slipping and lost.



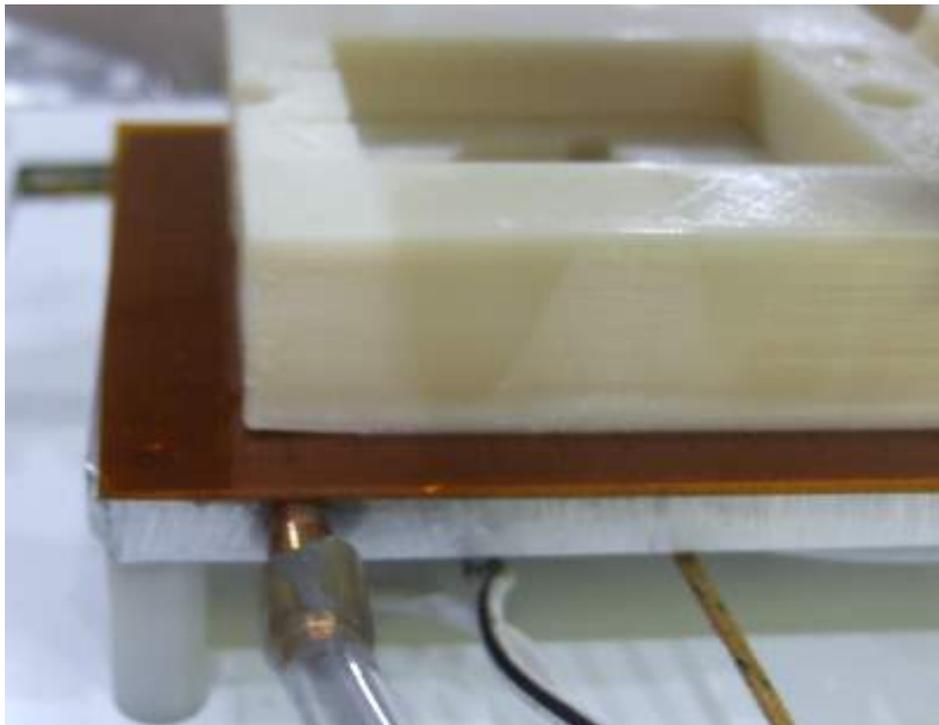
It did build enough to show that it sticks much better though. The corners stayed down and the build lasted long enough to go way past the point where the corners lifted on the vacuum bed. The base was perfect.



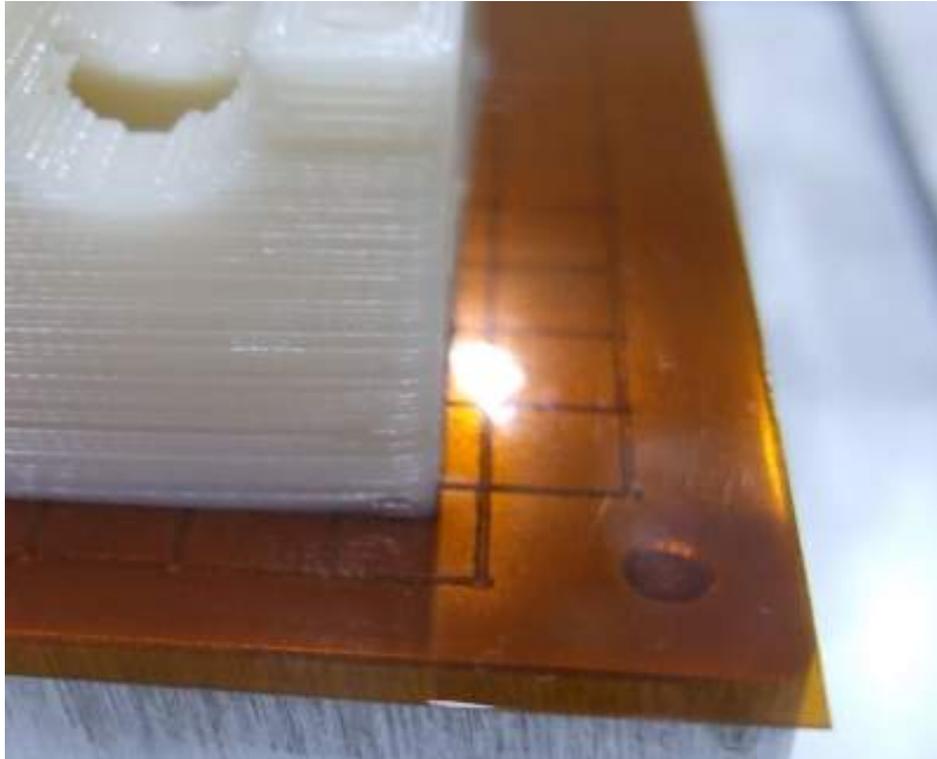
I could only think of three possible reasons why the corners would lift on the vacuum bed and not on the magnetic bed.

1. The surface of film might be different to tape. After all, tapes have the magic property that the glue only sticks to one side and peels from the other without leaving any residue.
2. The film is thicker, so has more thermal resistance, which might have some influence.
3. Perhaps the film can lift a little in between the vacuum channels allowing the plastic to peel away and then be sucked flat again.

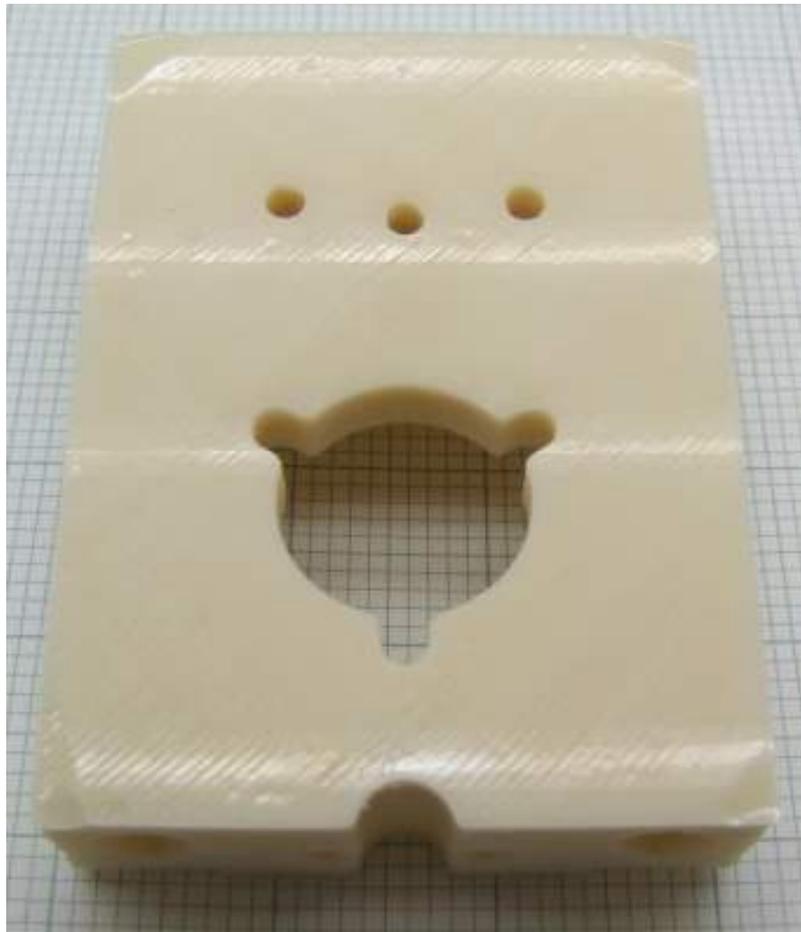
My best guess was that the third explanation was the most likely. Perhaps closer spaced channels or thicker film would solve it. I had a sample of 0.15mm film so that was the easiest thing to try next. It stuck much better but towards the end of the build I heard a snapping sound and saw that one corner had lifted.



More importantly though I could see that the other corners were deforming the film upwards as I had suspected. It is hard to see here, but the slightly raised blister of film was over a channel, so subject to the full vacuum force.



This shows that even with a heated bed, there is sufficient warping force at the corners to beat atmospheric pressure. The part ended up with one chamfered corner and dimples in the others.



So in general the experiment is a failure as it does not work as well as the magnetic bed. It does allow easy automated removal though. All you need to do is tape down one edge of the film. When the object cools it wrinkles the film and breaks the vacuum. A fence could then push the object off the bed with not too much force, as the film peels easily. When the object is gone the film springs back to being flat and the vacuum can pull it down again ready for the next object.

Although corners lift, the objects are usable for making a Mendel, it is only an aesthetic issue in this case. I think rounding the corners of the parts would fix it. I guess PLA might stay stuck as it warps less, and ABS only fails in extreme cases.

Thanks to Paul for providing the polyimide film samples and lending me the vacuum gauge.

# PLA on a vacuum bed

Thursday, 11th February 2010 by Nophead

Having successfully made one Mendel z-leadscrew-base\_2off as an experiment to try ABS on a vacuum bed, I decided to make the second from PLA to see how well that works on a vacuum.

Three of the corners lifted very slightly during the build (about 0.2mm) but not enough to matter except to a perfectionist.



When the object cooled it did not break the vacuum, unlike ABS. The part was still easy to remove though.

The base is flat apart from the corners and a few shallow dimples.



The quality was very good with no clean-up at all. I recently discovered a simple bug in all my builds after I moved away from 0.5mm filament. With 0.3mm and 0.4mm filament my layer height was 0.24mm and 0.32mm respectively. The problem is my z-axis only has 0.05mm resolution, so layers alternated in height, none of them being spot on. That caused the sides of my objects to not be as flat as they should be as the filament width varied from layer to layer. I now use 0.375mm filament giving a 0.3mm layer.

# PMMA on PI

Wednesday, 17th February 2010 by Nophead

Previously I described how I made some lamp shade clips for some friends from PMMA (Acrylic). Unfortunately the clips got lost in the post so I had to run off some more. I used a sheet of acrylic as the bed the first time, but since then I have developed my magnetic bed with PI (Kapton), so it was an interesting experiment to see if PMMA would stick to PI.

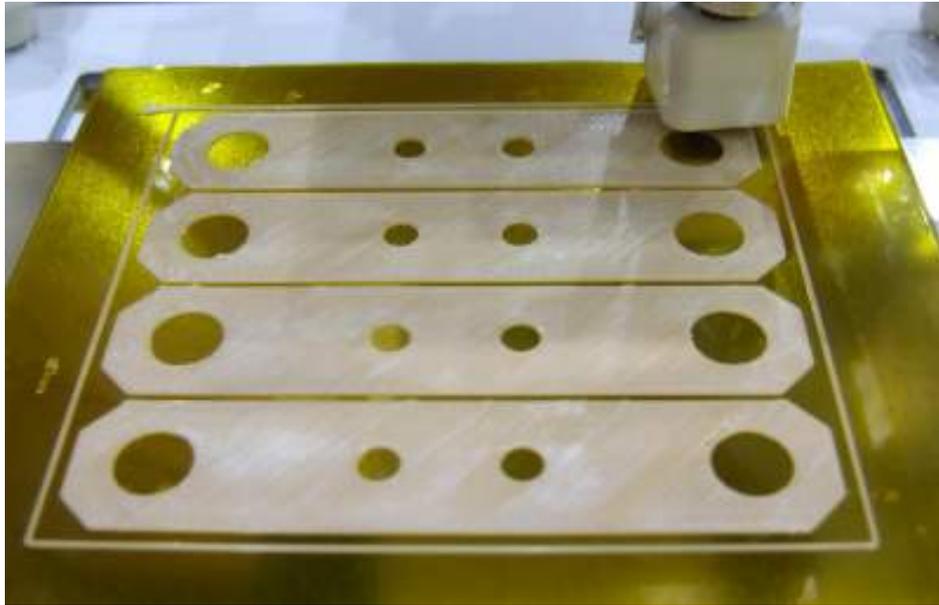
The originals were made with the bed at 100°C, but the insulating effect of 4mm of PMMA gave a surface temperature of only~85°C. That was sufficient to form a partial weld strong enough to resist warping. My first test was with the bed at 100°C, but that came loose after a few layers. With the other plastics I have found I need a higher temperature on PI because it does not form a weld. It sticks by some magic that I don't understand, possibly Van de Waals forces.

I tried again with the bed at 130°C and this time it stuck well but was easily peel-able by bending the bed. So another plastic that works on hot polyimide.



I have also been doing multi-part builds one layer at a time, something I hadn't dared to do until recently because my previous extruders were not reliable enough to risk a bed full of objects.

If you get the height just right on the polyimide bed the first layer comes out almost perfect. You can actually make one layer thick objects, i.e. 0.3mm in this case.

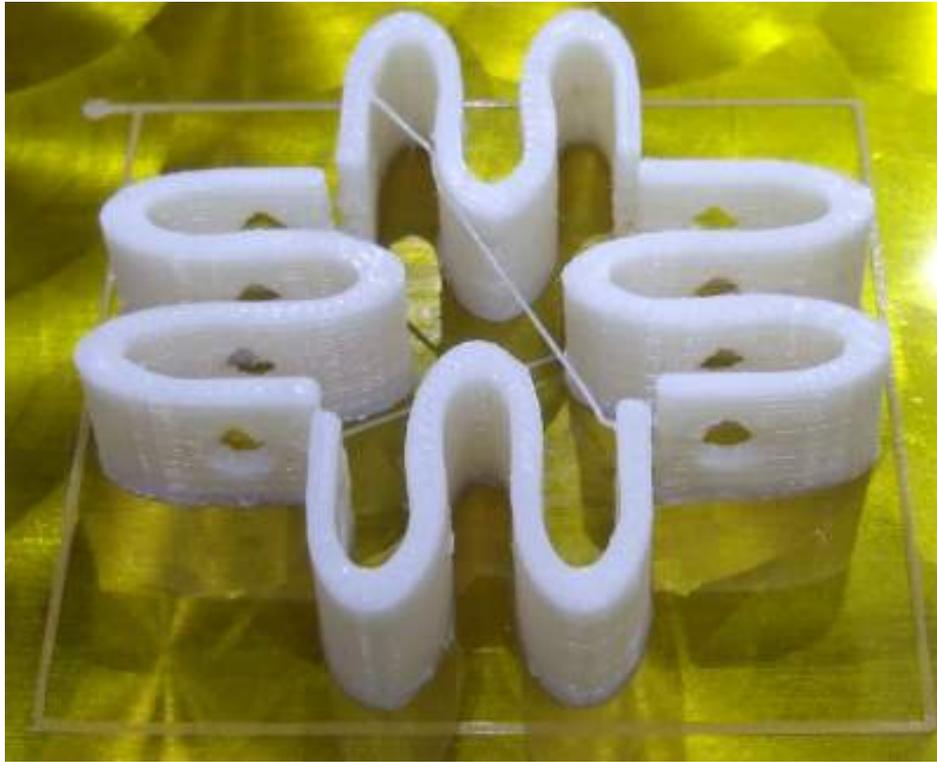


These came out very well.



I arrange multiple items by reading the STLs into AOI and orienting and positioning them. I then union them together in pairs and then union all the unions until I have a single object. I then convert that to a triangle mesh and export it as a GTS. If I don't convert first I only get one object in the GTS rather than the composite. I then slice as one object.

These springs show a very rare bug in Skeinforge or my code where it does a move with the extruder on. That is the only time I get any string.



Here is an assortment of smaller parts :-



It is best to group the taller parts together so when it gets to the higher layers the head does not have far to travel.



There were so many in this build that it overlapped the hot part of the table, so a few corners lifted a bit. I think ideally the table should be a bit bigger than the movement to keep some warm air around the objects. Perhaps a wall around the edge would keep some heat in.

I did have the crazy idea of building a wall around the objects as they are made so that there is a small gap of trapped hot air around them. I.e. the machine builds a disposable cocoon around the object to act as a heated build chamber. It would be a bit wasteful of plastic of course but it could be made from a cheap paste if we had a second head.

# Making Mendel

Sunday, 21st March 2010 by Nophead

I aimed to build my Mendel in time to show it at the Makerfaire in Newcastle but completely failed. I had two weeks to build it, which I thought was plenty. In actual fact it took closer to three weeks before I got it printing successfully. I had no major problems, just a few snags here and there and a severe underestimation of how long it would take on my part.

## Printed Parts

Unlike when I printed two sets of Darwin parts, printing the parts was the easy bit. This was due to three breakthroughs I had at the beginning of the year: -

- The heated Kapton bed removed the need for rafts, which not only take a significant time to print, but also can take a lot of manual work to remove.
- The extruder fast reverse got rid of all the strings, which also took a long time to clean up, especially from inside the Darwin corner blocks.
- The "no compromise" extruder is so reliable that I have the confidence to do multi-part, layer by layer builds, which gets a lot more on the table, allowing longer unattended operation.



I printed the parts with 0.4mm or 0.375mm filament and with 25% infill. For the larger parts I used two outlines for strength. Since the large parts don't need fine detail, I think printing them with 0.5mm filament and one outline would be quicker, but that would need a bigger nozzle.

The weight of the parts, not including the extruder, was only 730g. I printed the outlines at 16mm/s and the infill at 32mm/s, so it's hard to say the total time. Assuming an average speed of 24mm/s at 0.4mm diameter gives about  $3 \text{ mm}^3/\text{s}$ . That would put the total time at about 65 hours. I did it as a background task over a few weeks. A lot of the parts were printed as experiments with heated

beds.

## Rods

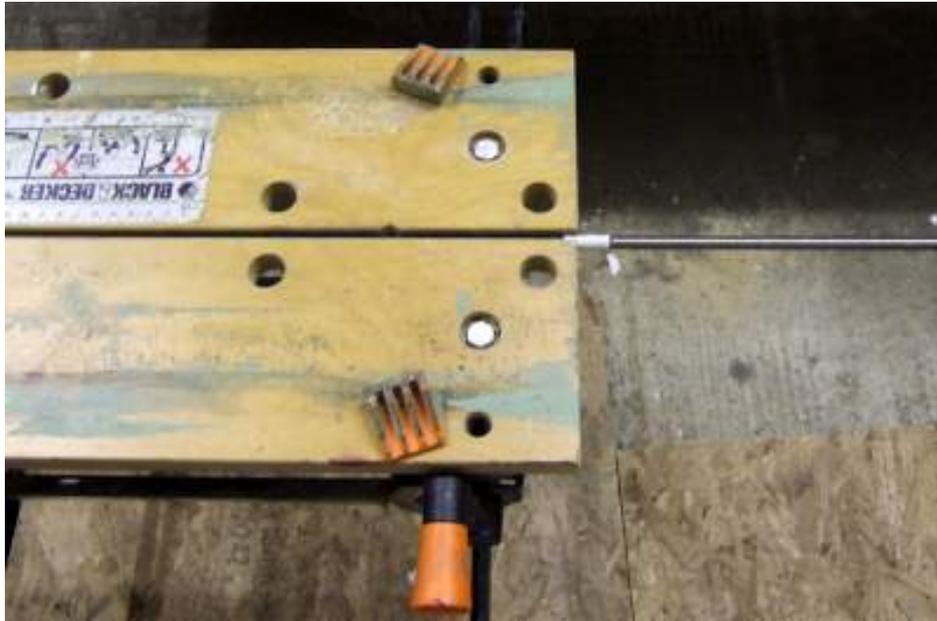
I took me an evening to cut all the rods. The method I used was to nail a stop to my workbench to line up the rod against a metre rule.



I then lined a piece of masking tape up with the correct measurement and wrapped it round the rod to mark the place to cut. I also wrote the name of the rod on the tape to make it easy to identify later.



A Black & Decker workmate makes an ideal vice to hold the rods while sawing. I rotate the studding until the thread lines up with the edge of the masking tape. That guides the saw to start in exactly the right place.



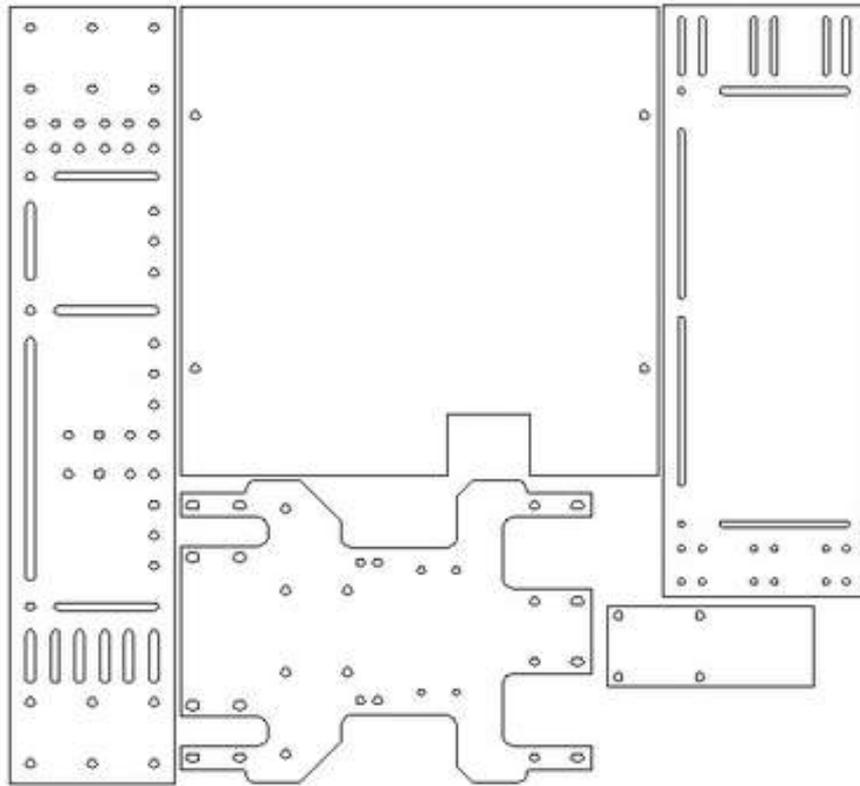
I used BZP for all the studding except the z-leadscrews, for which I used A2 stainless steel because it is smoother and generally straighter. I bought the rods from Farnell and even the BZP studding was very straight, a lot better than the stuff you get in B&Q. I also used A2 for all the bars.

It was very hard work sawing the A2 until I switched to a new blade and used Treflex cutting compound. I am not sure which made the most difference, but I could then cut the A2 much easier than I had been previously cutting the BZP. I wish I had done that earlier, it would have saved a few hours.



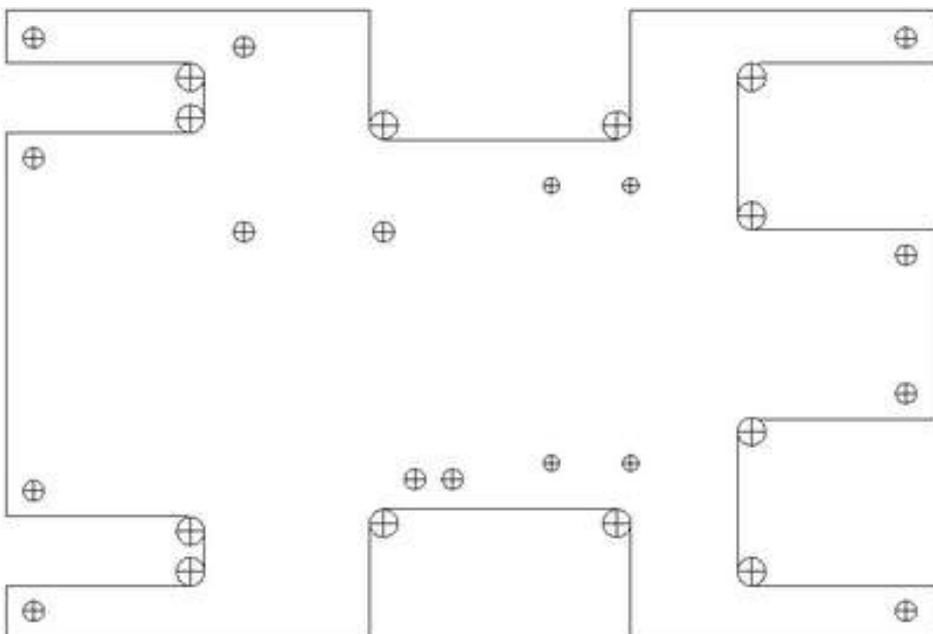
## Thick Sheets

The thick sheet parts are not really suitable for making by hand, particularly the squashed frog. They have lots of slots, which are hard to make without a milling machine or a laser cutter, etc.

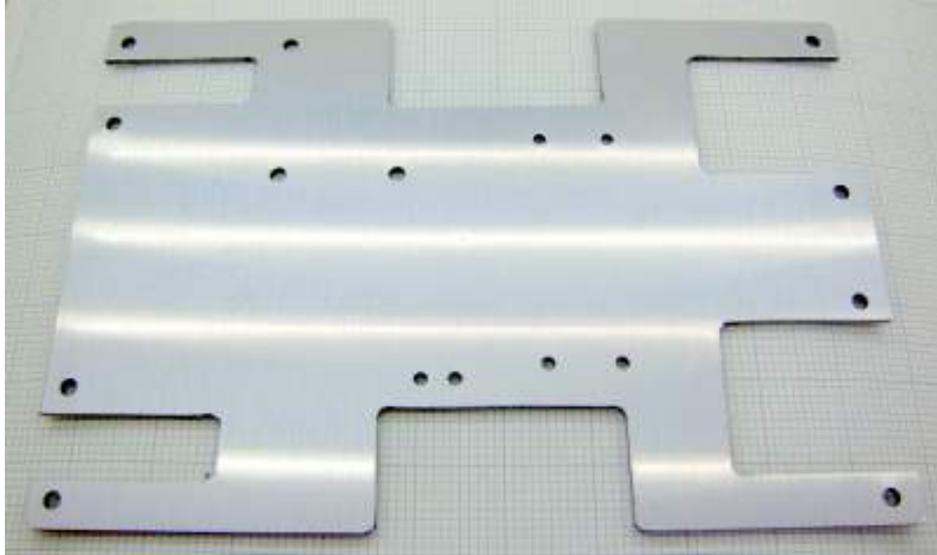


I am not sure exactly what the hole in the bed and the purge plate are for, so I made the bed a simple rectangle with four holes. I am using my own electronics, so I made the two circuit board plates to suite. I simply cut rectangles and I marked the holes and drilled them in the right place, so no need for slots. That just left the squashed frog.

I made a much simpler design with drill centres on it. There is no need for the bulging legs and sloping shoulders. I think they must be just to make it look more like a frog. Fine if you are CNCing it, but a PITA if you have to make it by hand. Also the holes for the opto tab and the purge plate are mirrored for no apparent reason, so I made it chiral.



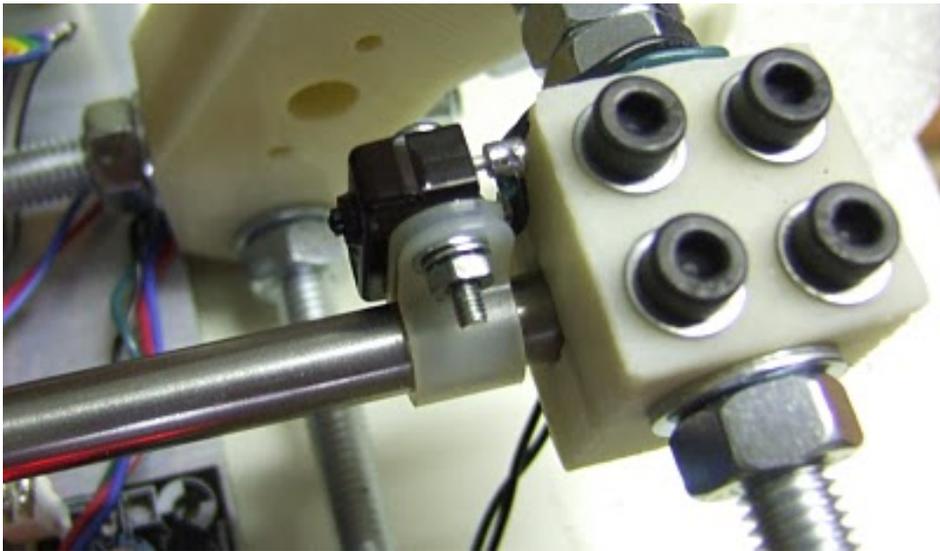
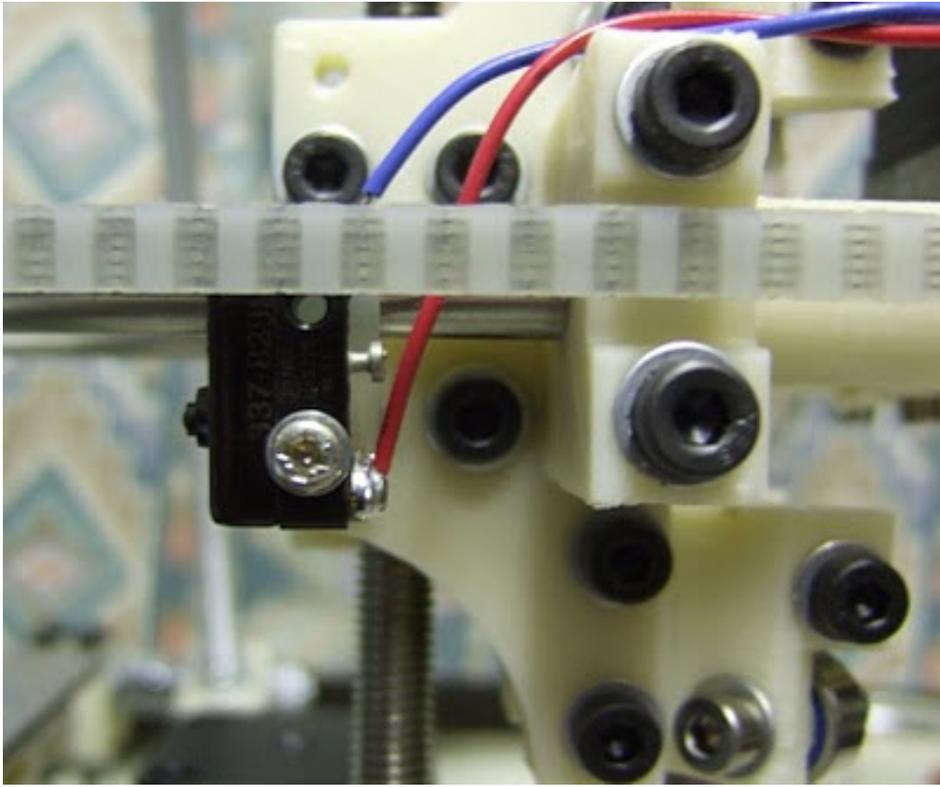
This just starts as a rectangle with some holes in it. Then the large slots are made with a saw thin enough to turn in the holes. The outer holes that mount the bearings can be round because they are in a fixed place, dictated by the holes in the bed. The inner holes need to be slots because the bearings are adjustable. I just left them off the template and marked them with the bearings adjusted and in place.



I made the sheets from 3mm Dibond, which is below the recommended thickness, but seems stiff enough. It is also light weight and very easy to machine.

## Thin Sheet

I didn't have any optos, so I used micro switches for my end stops, hence didn't need any thin sheet parts. I simply attached them to the bars of each axis with P-clips. A little RepRapped bracket would be better but I was building this in a hurry, so had gone into bodging mode at this point!





They seem to have sufficient repeatability and certainly will when I replace the electronics with my new design, which will know the motor phase, reducing the uncertainty by a factor of 32. It is the same switch that I have used on the z-axis of HydraRaptor, which has proven totally reliable. They seem to be this one from RS, not cheap.

## Belts

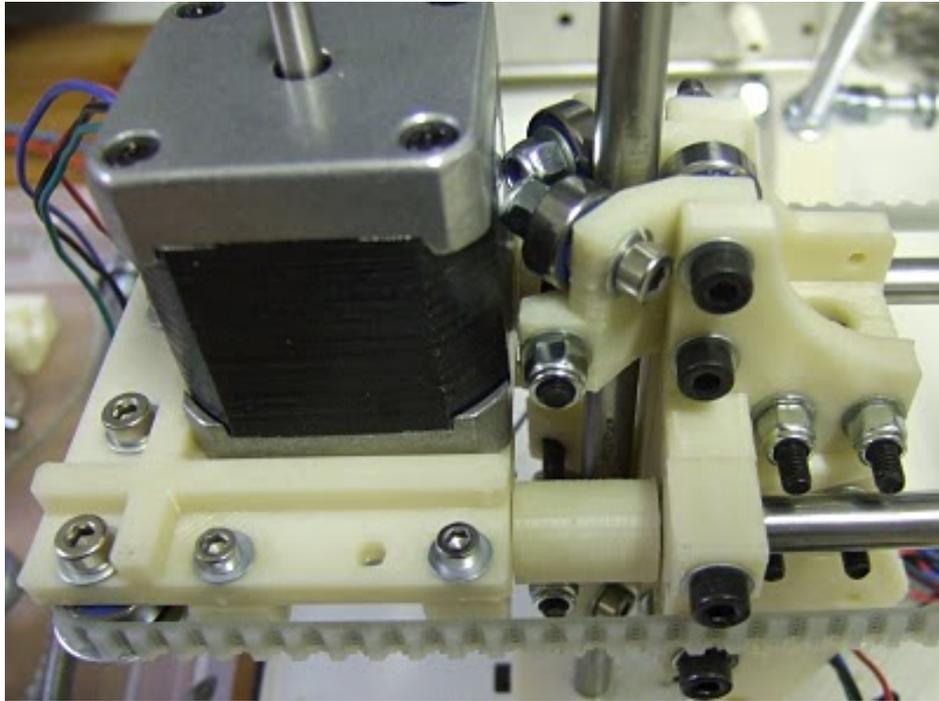
These were easy enough to split but, because the reinforcing wires run in a spiral, the blade tends to follow one for a while before managing to cut through it. That leaves a ragged edge with a bit of wire sticking out.

I didn't understand the rationale for slackening the belts until you just don't see backlash when moving one motor detent. I am microstepping anyway, so a motor detent is not significant. I made my belts good and tight.

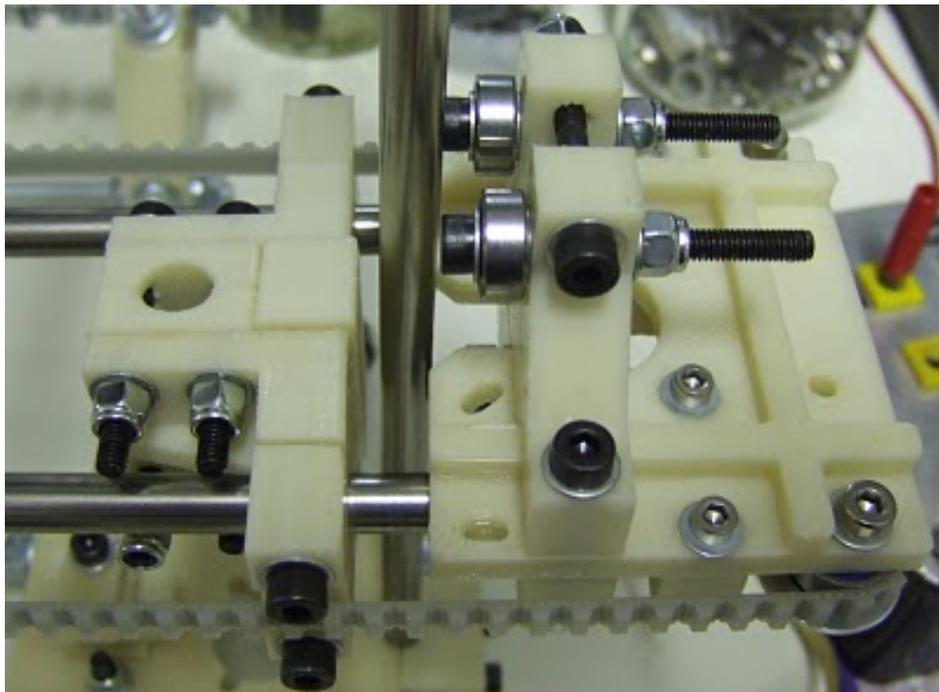
## Snags

I had a few snags with the mechanical assembly: -

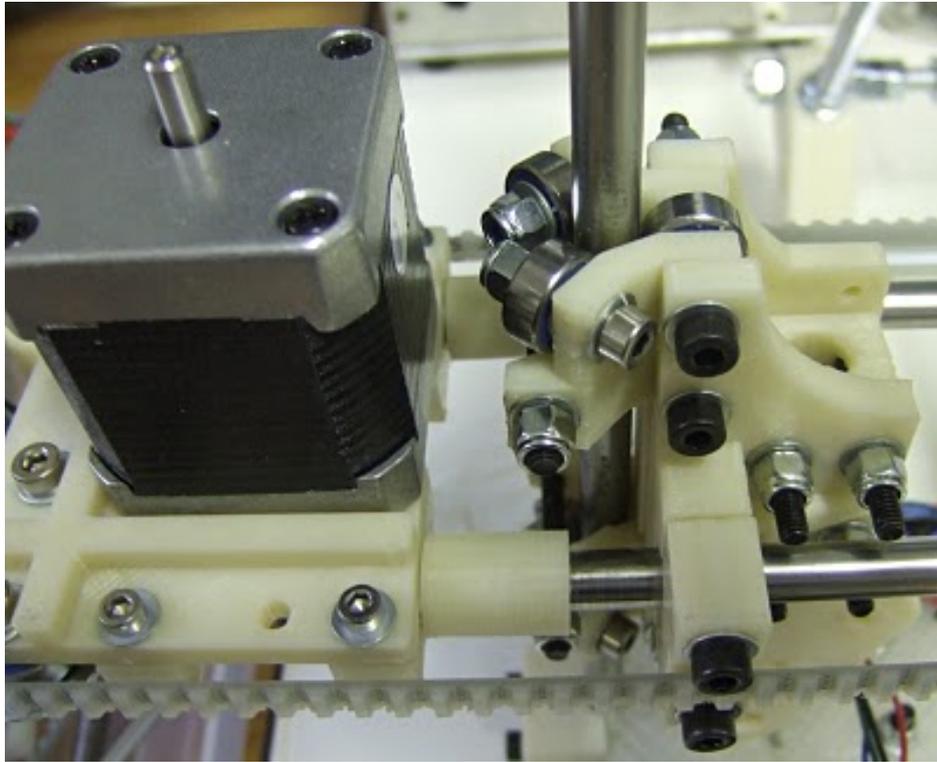
The x-axis spacers are too short. The STL files are 5mm shorter than the parts in the STEP assembly. That caused the motor to clash with the nuts on the 360 bearing.



The 180 bearing at the other end was about 10mm from where it should be.

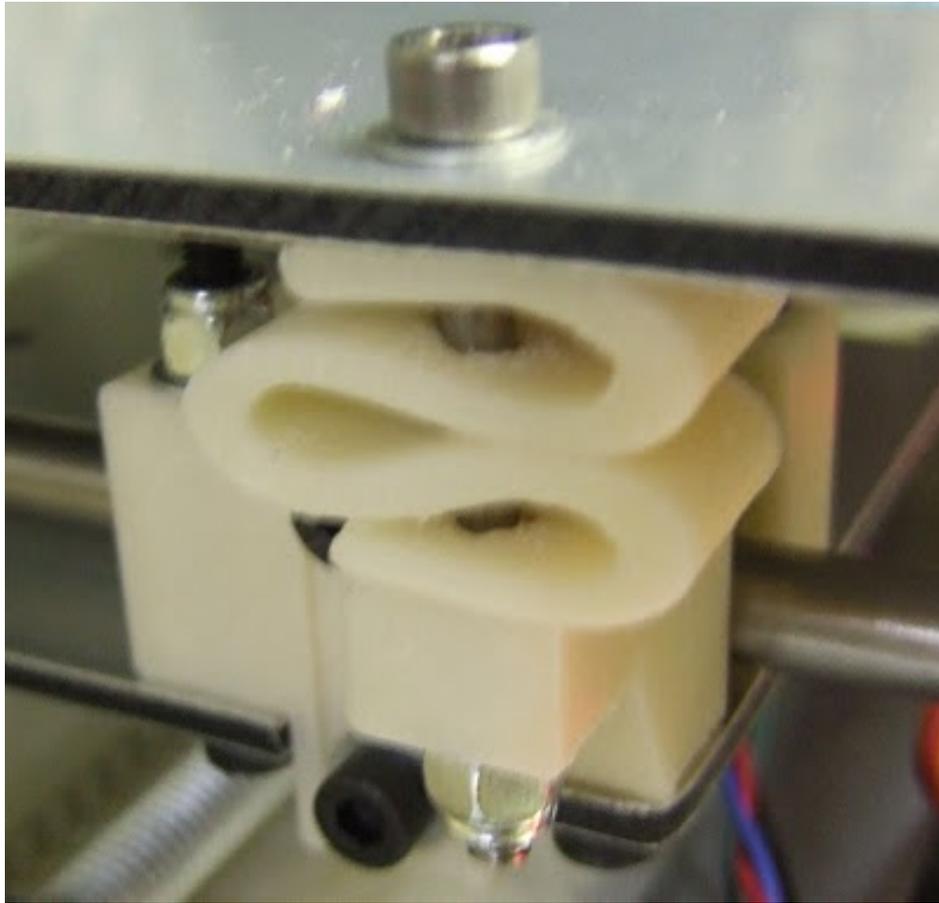


A simple fix was to slide the axis along leaving a 10mm gap to the spacer, the only problem remaining is that the spacers rattle at certain step rates.

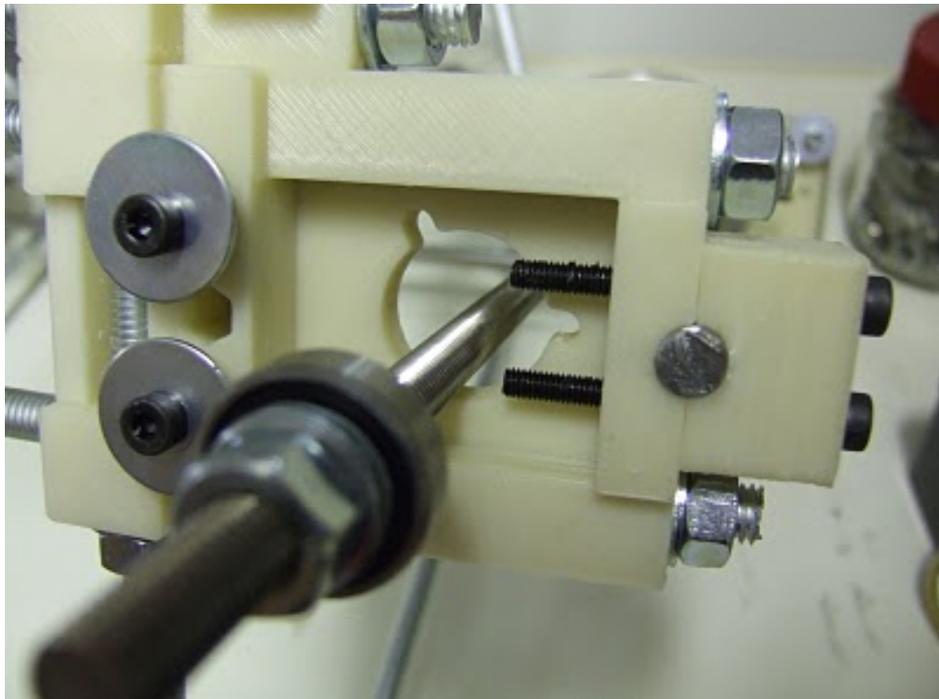


The STEP model shows this gap should be only 5mm, but I have been unable to find the discrepancy. My rods and inspection distances are correct and the ends of the rods are flush with the clamps, as they are in the model.

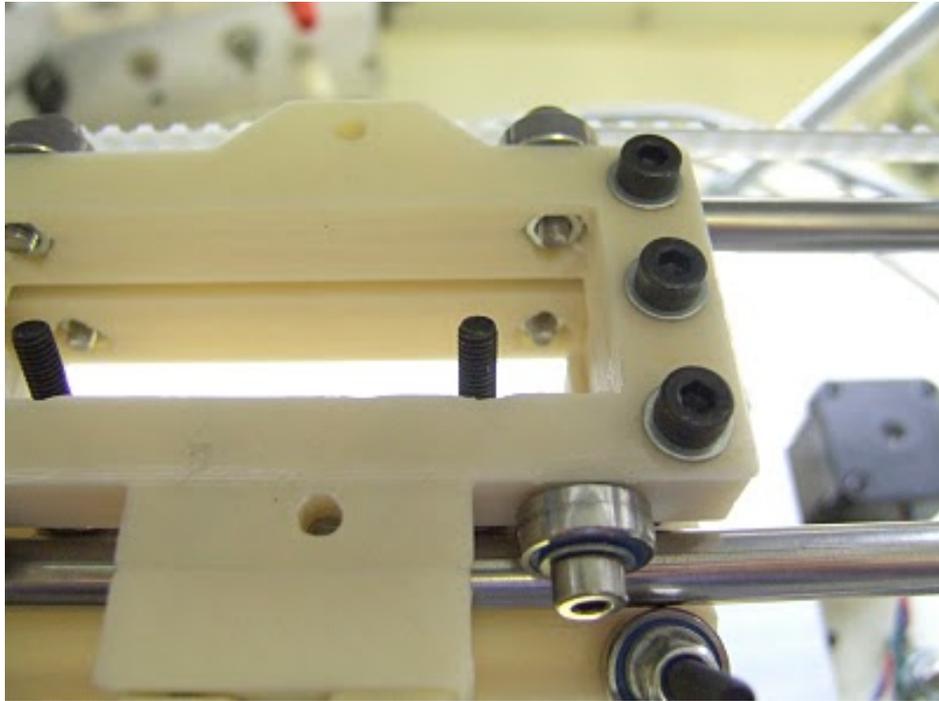
The bed springs seemed to be too long to compress to the length of the bed-height-spacer-31mm\_1off, which is not actually 31mm, but 29mm, so I don't know what gives there, I just spaced them a bit higher.



The bolts in the z-bar clamps are too long to allow the bearing to be inserted. I replaced them with shorter ones.



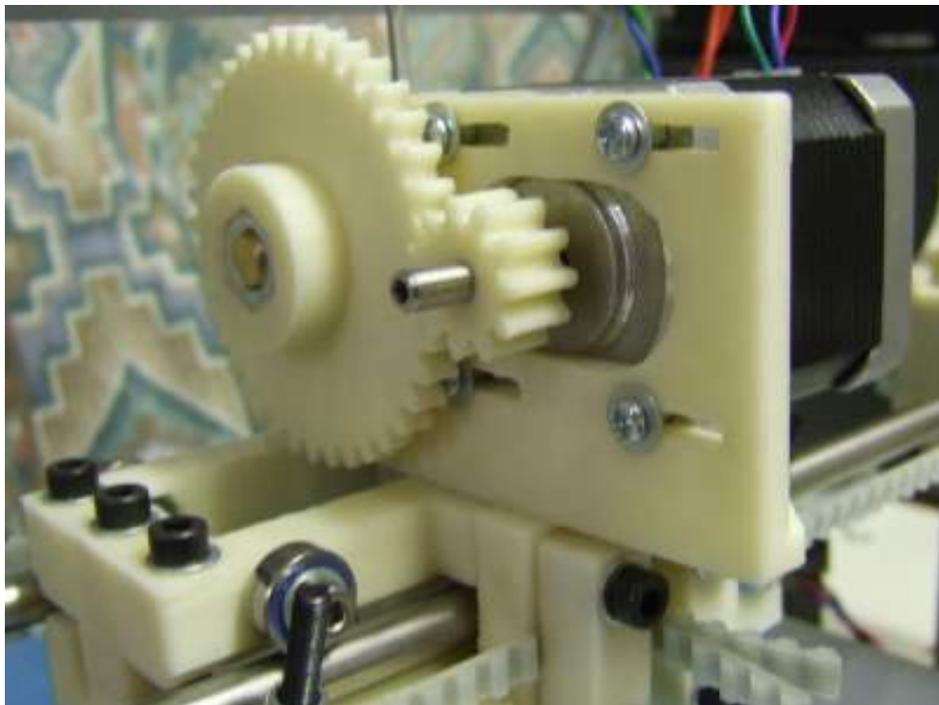
Similarly the bolts in the x-carriage get in the way of the extruder I fitted.



The J3 jugged distance did not seem correct. The distance between the y-bars is set by the J2 distance and the 3 nut spacers.

## Extruder

I used Wade's extruder design as I didn't have time to adapt any of my own.



The gears work well, with very little backlash, but the small one has some movement on the motor shaft. It is just a press fit with a flat on the shaft. I need to redesign it with a captive nut and grub screw.

I didn't have a suitable M8 shoulder bolt so I made one from brass by attaching a nut with a pin through it.



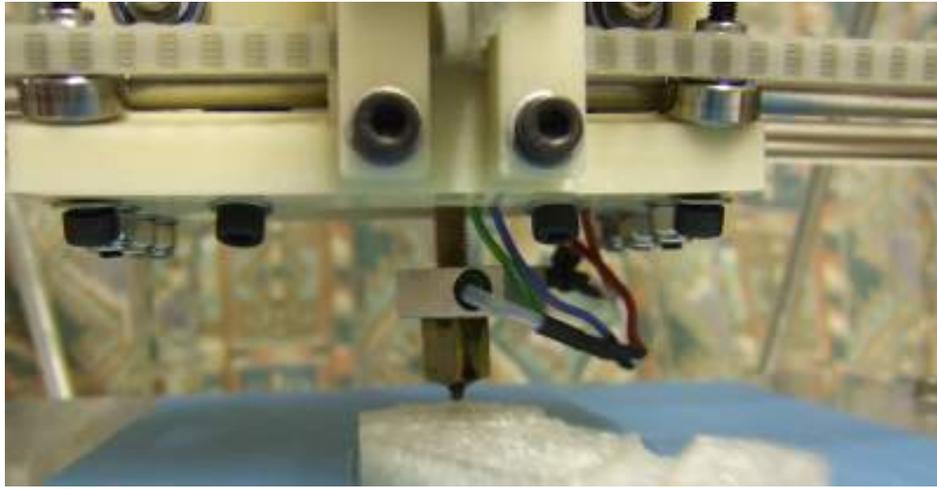
I hobbled it with an M3.5 tap. I haven't measured the grip, but I get the impression it is not as high as Wade gets, I am not sure why.

For the bottom half of the extruder I used some parts that Brian was looking for volunteers to test for him.



The insulator is made from PEEK with a PTFE liner. The idea being to get the strength of the PEEK and the slipperiness of the PTFE. It seems to work well with PLA, which is all I have run through it so far.

The barrel is long because it is designed to take nichrome, but I just screwed it into a block of aluminium with a vitreous enamel resistor in it.



This was left over from a previous experiment. I have now moved onto a smaller resistor size, so this block could be smaller. The barrel could be a lot shorter with this arrangement and that would give less ooze and less viscous resistance.

The extruder works well with PLA. The main problem with it is that it mounts at right angles to the x-axis, so the motor severely restricts the maximum height of the z-axis. Another issue is that to remove it you have to remove the motor to get at the bolts. To remove the motor you have to remove the big pulley to get at the motor's bolts, to do that you have to remove the pinch wheel assembly. I.e. to remove the extruder you have to completely disassemble it!

## Electronics

To get up and running quickly I used the same electronics that I use on HydraRaptor. The only difference being that I used MakerBot V3 stepper drivers. These use the A3977 chip and give x8 microstepping. That gives an axis resolution of 0.025mm, but more importantly gives nice smooth running.

When the weather was exceptionally dry I found they are very sensitive to static. A discharge to any part of the machine would cause the A3977 to shut down its outputs and draw enough current from the 5V rail to cause the 100mA regulator to current limit. The red LED on the power rail goes dim. Powering off and on again fixes it and there doesn't seem to be lasting damage. I suspect that might not be the case if the 5V rail was not current limited. Apparently the only way to fix it is to add external Schottky diodes. That is very disappointing as one of the nice features of the chip is that it is supposed not to need them. I will investigate further to see if all eight diodes are needed before making my own board.

## Firmware

I used the same firmware as HydraRaptor. I just added some compile time conditionals to cope with two pin outs and a different IP and MAC address for each machine. I also had to change from 16bit to 32 bit positional commands because the axes are bigger.

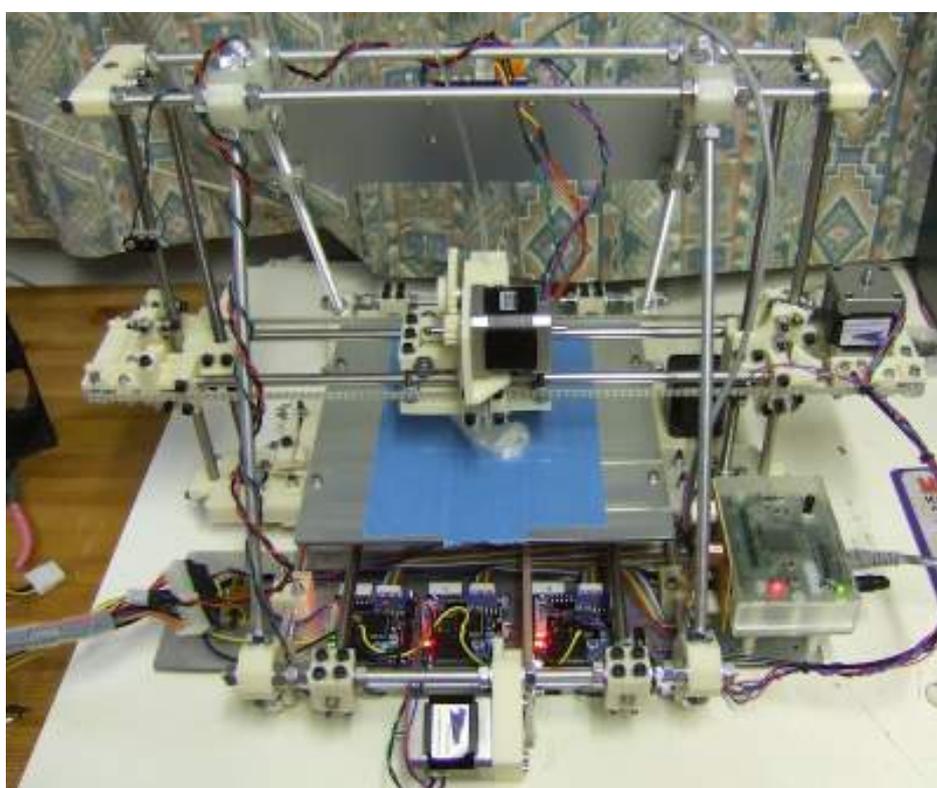
## Software

I used the same Python software as HydraRaptor but I had to re-factor it quite a lot to support both machines. I added a class to represent the Cartesian bot which holds the axis resolution, direction, maximum speed and acceleration plus the IP address. I also added a class to represent the extruder controller as I have calibration values unique to each board. I already had classes to represent thermistors and extruders.

I can run both machines at the same time from one PC and, because I only use the Skeinforge output for the toolpath, I can use the same sliced files for either machine. This is despite the fact that they run at different speeds and are loaded with different plastic.

## Results

So here is the finished machine: -



And here is a video showing it being tested: -

I am running the X & Y motors at about 0.75A and Z at about 1A. I have set the maximum XY speed to 100mm/s, but I think it could go a lot faster. Z only goes at about 5mm/s because not only is it a threaded rod drive, but it is geared down by the belt and pulleys!

I haven't printed a lot yet, but so far the results look as good as they do from HydraRaptor. The next thing to do is add a heated bed and try ABS.

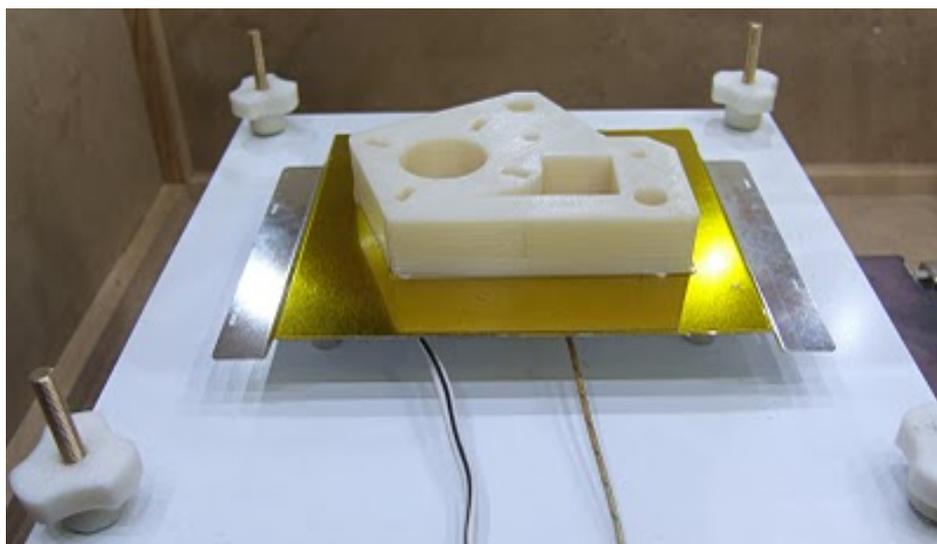
# Heated bed MK3

Thursday, 25th March 2010 by Nophead

My first heated bed worked OK but it was slow to warm up and hard to remove objects.



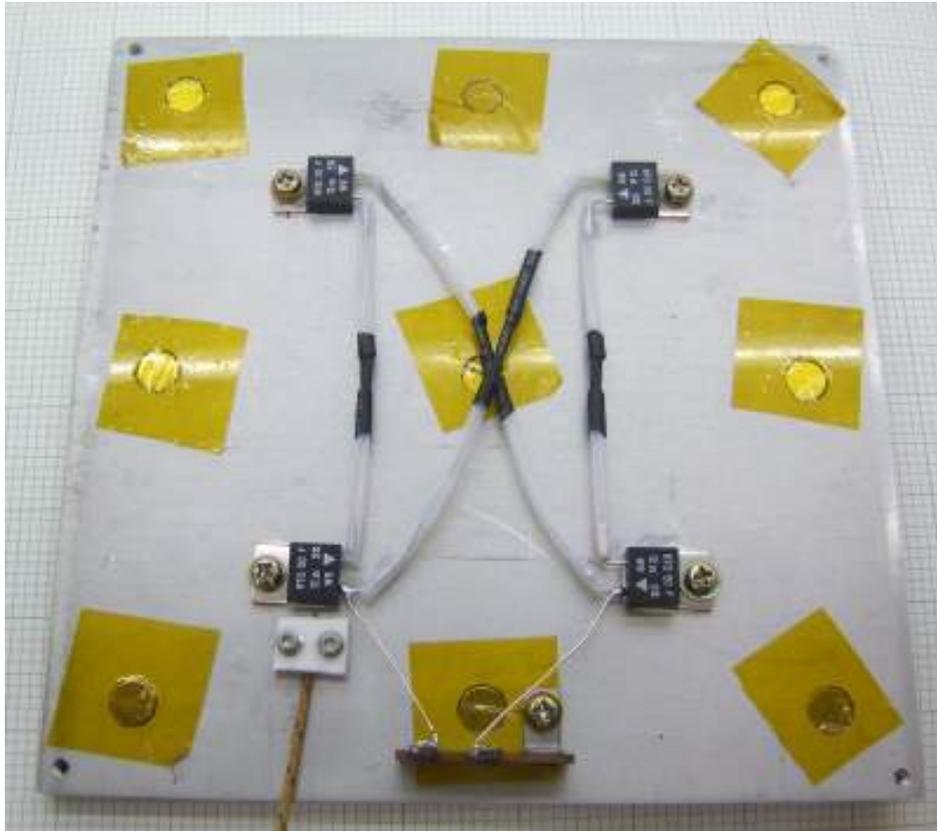
The second one was only ever intended for experimenting with vacuums and magnets but I ended up printing most of my Mendel on it. It worked well but limits the build area.



I have now replaced it with a full size version, using the lessons learned from the first two.

The first bed was the same size as HydraRaptor's table (200 200mm) but the build area is only about 150 150mm. The warm up time and power are both proportional to area, so I made this one just big enough, i.e. 150150mm. Removing the 25mm border nearly halves the area!

The other innovations were to make it easier to build. I replaced nine AL clad resistors with four TO220 resistors. These are rated at 50W and 155°C, so are actually totally within spec when I run the table from 48V giving 188W. Instead of having to tap two M2 holes for each resistor these only need a single M3 hole. That is much easier to tap as the tap is a lot sturdier.

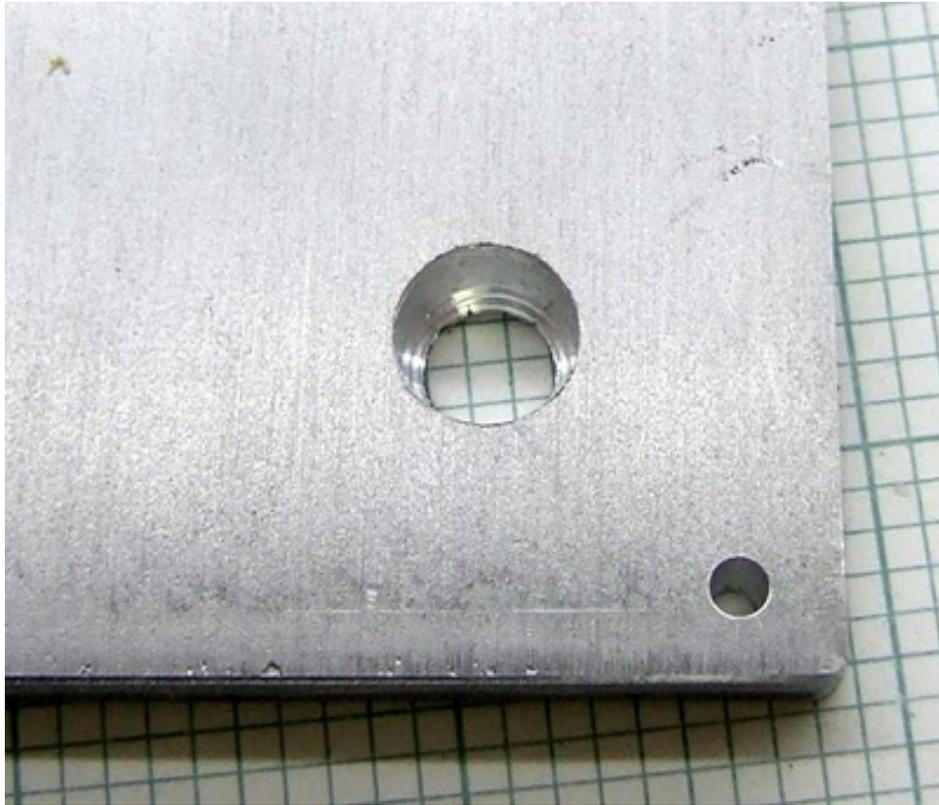


They are also lower profile of course. I just noticed that 47 ones are less than half the price, so I should have used four of those in parallel instead.

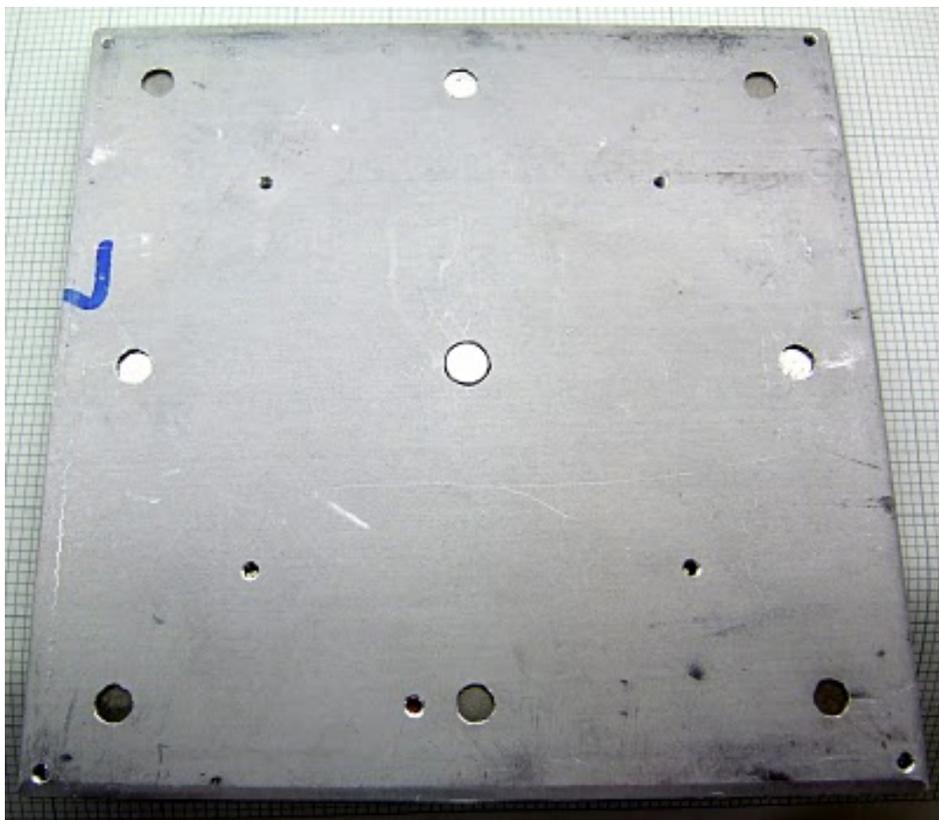
The thermocouple is mounted with a clamp made from PTFE.

Since this bed has a steel plate on top none of the holes need to be blind. That makes drilling and tapping easier as well.

On my previous magnetic bed I placed the magnets in blind holes that were almost all the way through. That required a milling machine to get flat bottomed holes. On this version I just drilled almost all the way though, leaving a lip to retain the magnet.



This is the top side. The magnet in the middle was done with an alternative technique. I drilled a through hole and then jammed the magnet in with a few strands of copper wire. That gets it flush with the surface, giving maximum magnetic force, but it pulled through on first use. I will have to glue it with high temperature epoxy I think.

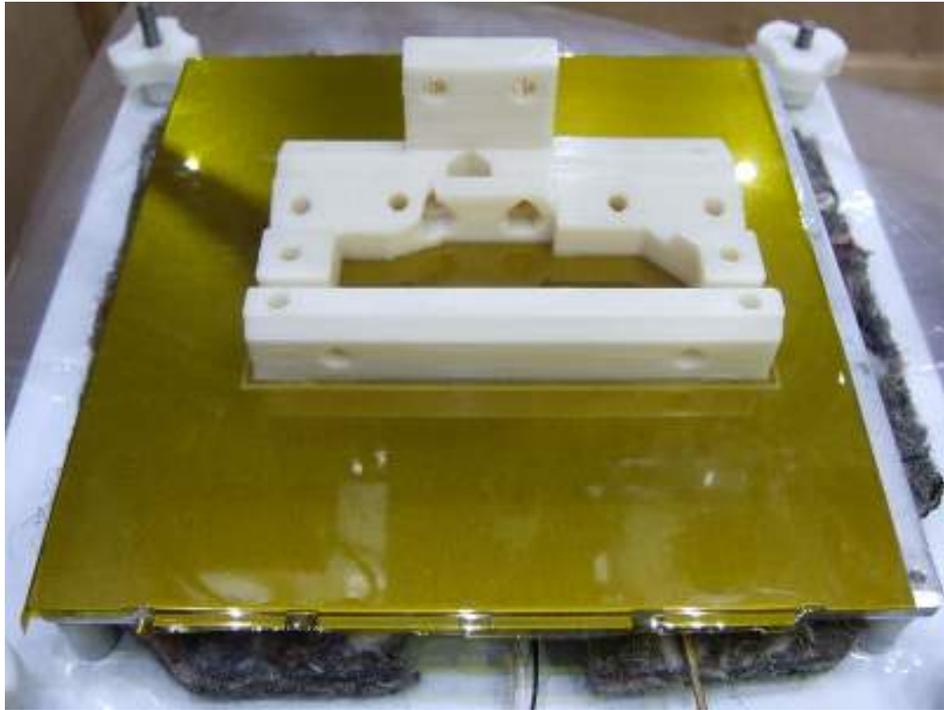


After a suggestion by Enrique that wool was a good high temperature insulator my friend Steve gave me some carpet underlay made from wool. I used it to insulate the underside, thanks guys.



For the steel plate on the top I used the cover of an old CD ROM. It is only 145mm wide unfortunately. I think it is mild steel with nickel plating. Not as good as the stainless steel springy piece I got from inside a toaster.

So here is the finished article with the biggest bit of Mendel built on it. It was quite hard to remove. I had to remove the steel plate and bend it a little as intended. I had found that things I built recently on the small table could be removed without lifting the plate. I think the Kapton gets less grip as it ages. I tried cleaning it with alcohol and sanding it with very fine emery paper, but that seemed to make it worse if anything. It seems that shiny Kapton gives more grip than matt.



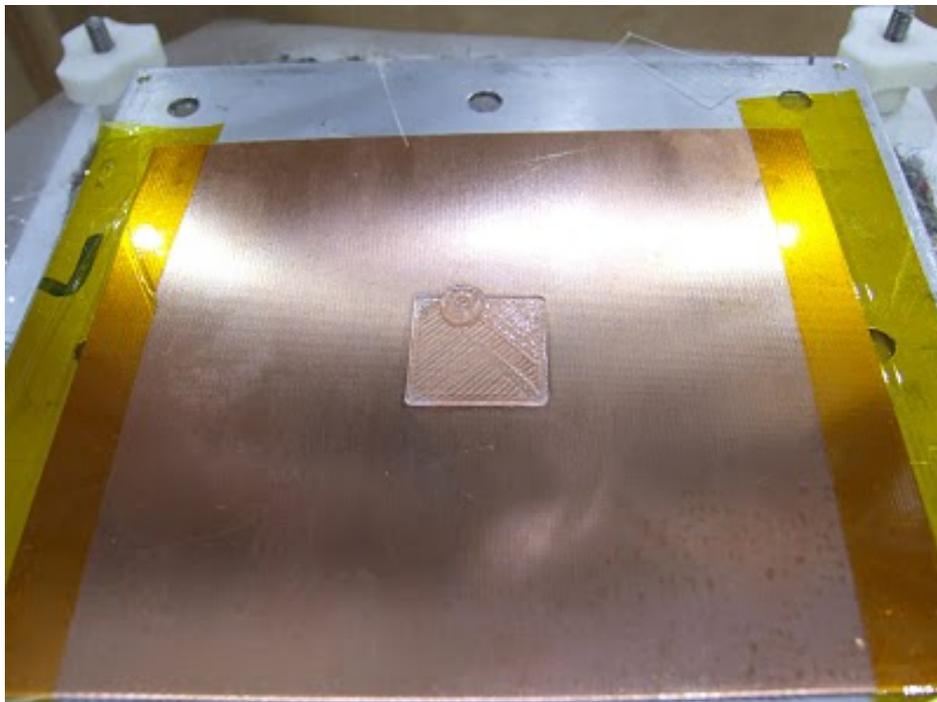
# CU + PLA

Friday, 2nd April 2010 by Nophead

Vik Olliver asked for a volunteer with a heated bed to see if we can extrude onto copper clad board. I didn't think it would stick, but gave it a go anyway.

I first tried ABS onto double sided copper clad FR4 taped to a bed at 120°C. The ABS stuck well enough to extrude the first layer of a 20mm square, but when it cooled down it had no adhesion at all.

PLA at 55°C did exactly the same, but PLA at 130°C stuck very well, so well in fact that I can't get it off with my fingers (the blob was where I aborted the print after the first layer).



Maybe ABS would stick in the same way at an even higher temperature, but maybe not as it is less like glue than PLA. The 120°C / 55°C temperatures are what I use for Kapton, which is why I used them as the starting point.

An interesting aside: I had to measure the PCB to work out the z-height. It is only 1.4mm thick, whereas a standard PCB is 1.6mm. You can also see the grains in the FR4 showing through the copper. This means the board I bought in Maplin for home PCB use is actually the same stock material that they use for the first part of a commercial production process, but when they plate through the vias they increase the thickness of the copper all over to get the standard 1oz/inch<sup>2</sup>. I don't know if this is always the case, i.e., that all home made PCBs have less copper than a production one, or whether you can get bare board with 1oz on it already.

Anyway a good result, assuming PLA will resist PCB etchant. Also, it seemed like a potential bed

technique. I.e. do the first layer onto hot copper and then cool it to about 50°C for the rest of the object. I tried it with this butterfly: -



It worked perfectly. After the first layer I blew it with a fan to cool it down to 50°C. It took about four layers to get down to that temperature. Since I added the insulation under the bed it takes longer to cool it than it does to heat it.

After it had finished and cooled down to 40°C it was still firmly attached, so I removed it by flexing the PCB.



The base of the object is perfectly flat.



I think for PLA this might be a better technique than Kapton. I can't imagine the PCB wearing out. It could also be self heating with a serpentine track on the other side. I don't know that just taping it down would be strong enough for making large objects. I could solder fastenings on the back if not.

I don't know if there is anything special about copper and PLA, or whether other hot metals and plastic would work . I tried similar things with ABS on AL, but may not have had it hot enough.

# Dibond bed

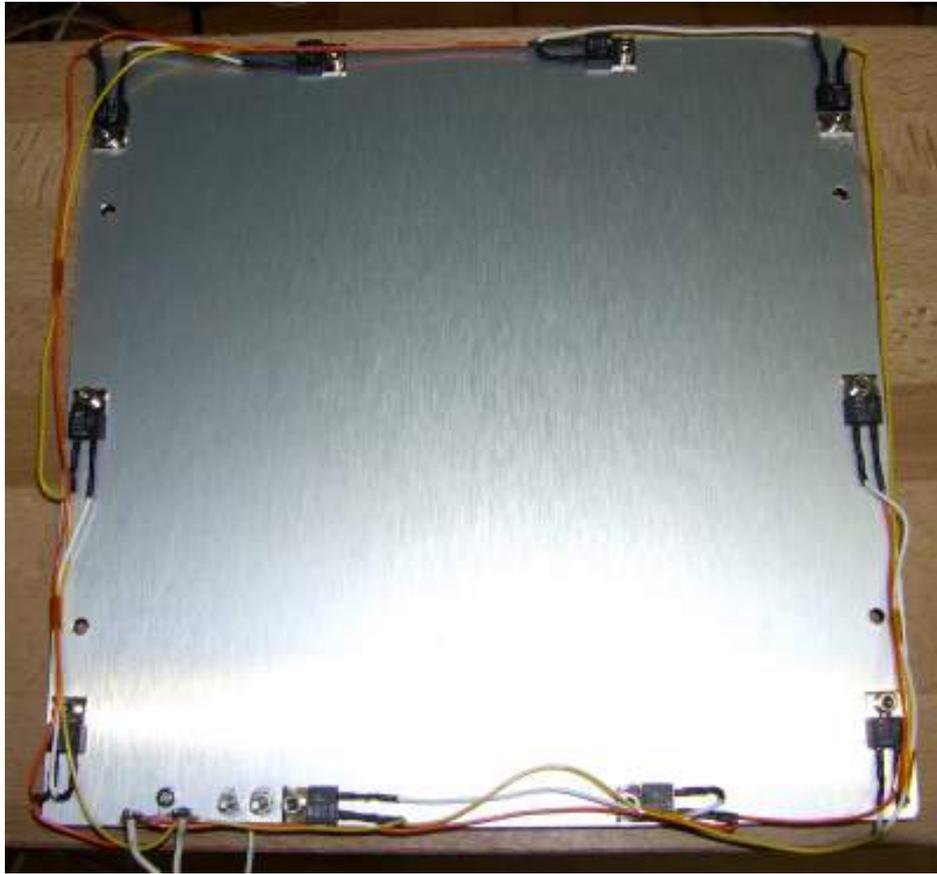
Tuesday, 6th April 2010 by Nophead

I had been making Mendel parts with my Mendel, using PLA on blue masking tape, as it didn't have a heated bed. When I made a frame vertex on its own it came out completely flat. Larger parts like the z-base brackets warped a little at the corners, but were still acceptable. However, when I made a bed full of parts the warping was much worse. Frame vertexes warped a little and z-base brackets curled up several millimetres and jammed the y-axis, ruining a bed full of parts. I think the reason they warp more is that it takes so long for each layer that the parts are completely cold when the next layer is deposited. The odd thing is that Adrian Bowyer manages to print trays full of parts on blue masking tape without a heated bed. I have added it to the growing list of things that work better in Bath than they do here: AOI and PTFE being another two.

I had some aluminium plate on order but I wanted to knock something up quickly. I figured PLA on blue tape would only need 40-50°C to stop it warping. My bed is made from Dibond, which is 3mm thick and has the following characteristics:

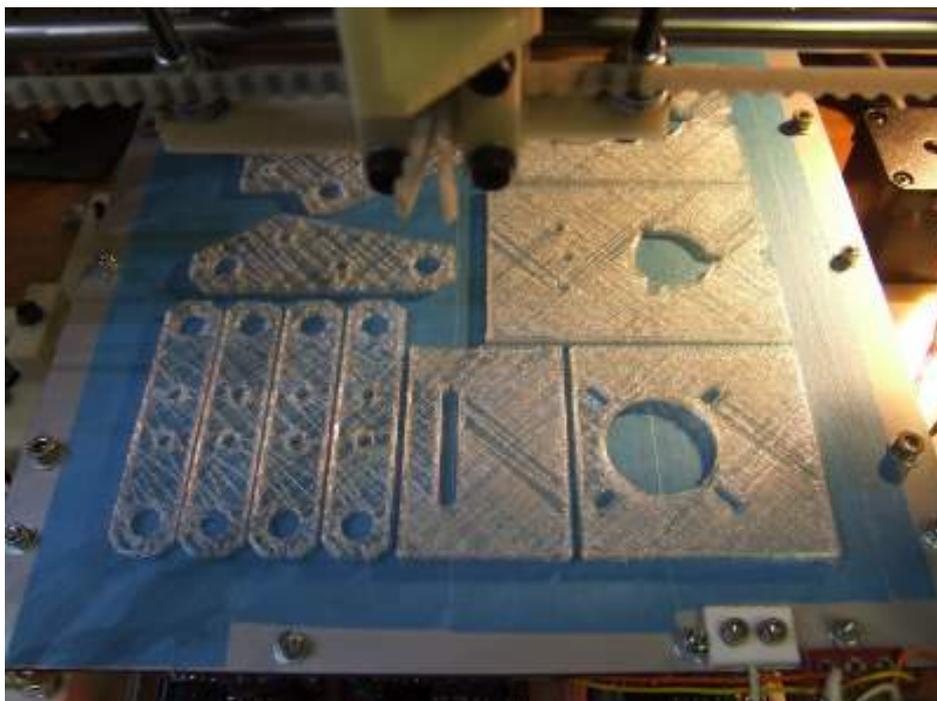
- Thickness of aluminium layers 0.3mm.
- Core polyethylene, type LDPE.
- Surface: lacquering - modified polyester lacquer system.
- Temperature resistance from -50 ° C to +80 ° C.
- Aluminium grade premium A1Mg aluminium alloy.

The great thing about it is that it appears to come pretty flat and is strong, light and easy to machine. I wondered if the aluminium layer was thick enough to spread the heat. I didn't think heat would flow though the LDPE very well so I mounted 10 47 50W resistors around the top edge. I have found that for some reason 47 are cheaper than the 12 ones I used on HydraRaptor's bed. I wired them in pairs in series and then all the pairs in parallel giving 18.8. I connected them to my 48V AC transformer with a small solid state relay. The total power is about 120W. Not as much as I use on my aluminium beds, but plenty of power to get to 50°C quickly. In fact, it warms up faster than my extruder does.



An initial test showed that the middle was about 10°C cooler than the edge. Not a big surprise considering how thin the aluminium is and how far the heat has to travel. When I measured the other side the difference was only about 5°C, so I decided to mount it upside down with the resistors on the bottom and the thermocouple on the top.

It works very well, and the objects stay flat. The first multi-part build I did though failed after the first few layers.



The extruder jammed because the top of the thermal insulator got hot enough to allow the PLA filament to go soft before the entrance. The extruder was finding PLA very hard to push anyway and the maximum speed I could get was about 24mm/s of 0.5mm filament. This is because the thermal transition zone is too long. The extra heat rising from the bed must have pushed it over the edge, literally!

The insulator is a combination of PTFE for slipperiness and PEEK for strength, but I think PEEK conducts too much heat. It doesn't help that my heater is not insulated yet and the Mendel carriage traps any rising heat.

I am quite happy with Wade's drive mechanism but decided it was time to try another hot end design, coming soon ...

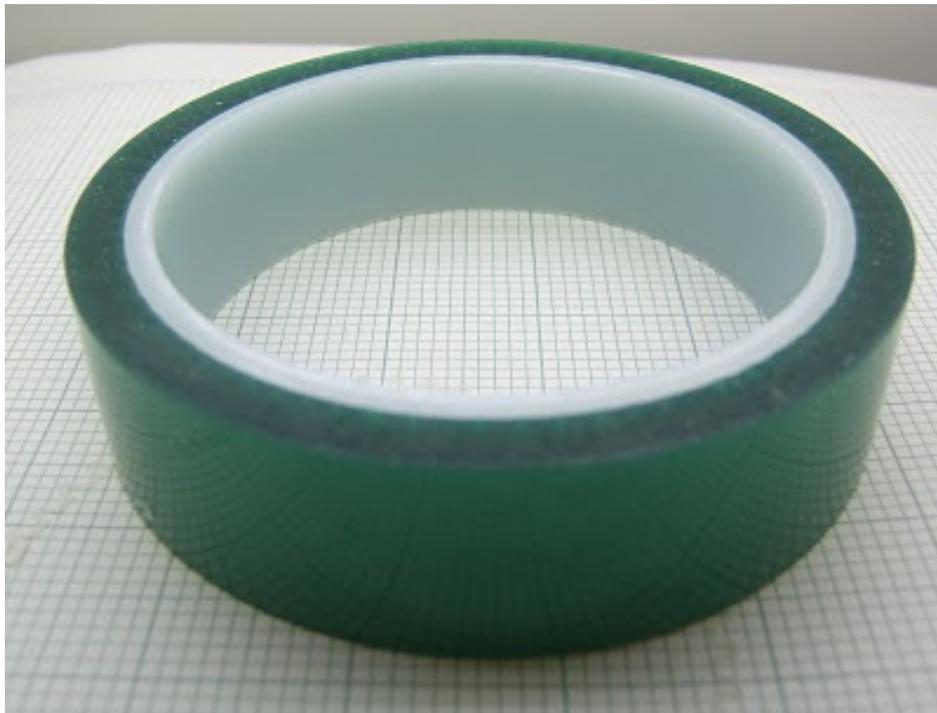
I think that for PLA, Dibond and blue tape / Kapton is a good solution. It won't handle the temperatures for ABS on Kapton though, but it might be good for ABS on PMMA or PC.

# ABS on PET tape

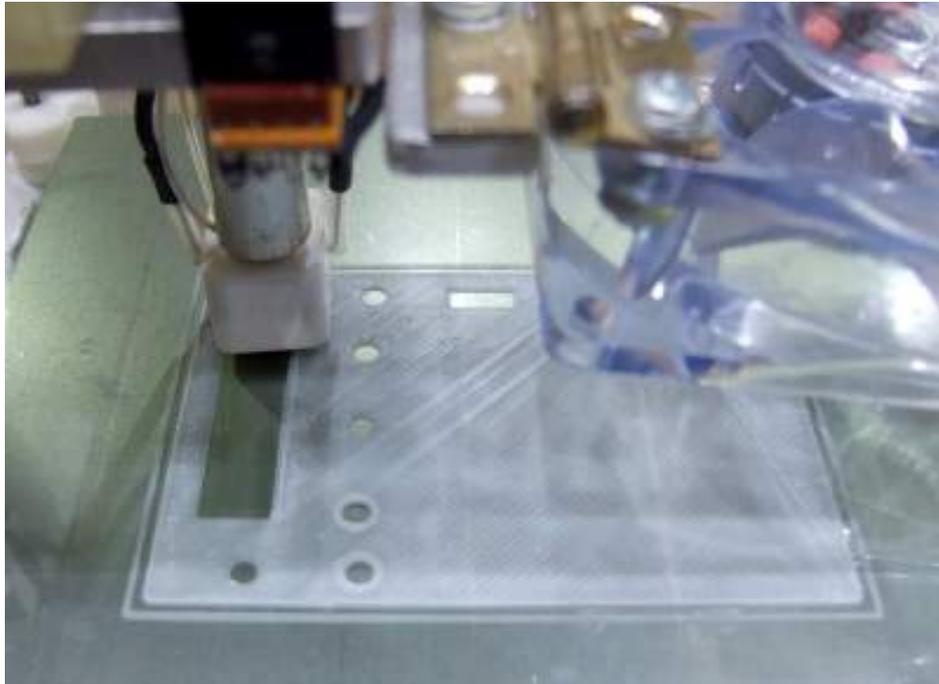
Saturday, 24th April 2010 by Nophead

I find ABS sticks to Kapton very well to start with, but as it ages, it seems to stick less well. Corners start to lift and eventually builds are ruined. I have tried cleaning it with isopropyl alcohol and with acetone but it makes no difference. Charles Pax has reported that sanding with 220 grit paper makes it stick better. I cannot reproduce this. In fact, I find the opposite effect. It always sticks well when new, and if anything, sanding it makes it worse.

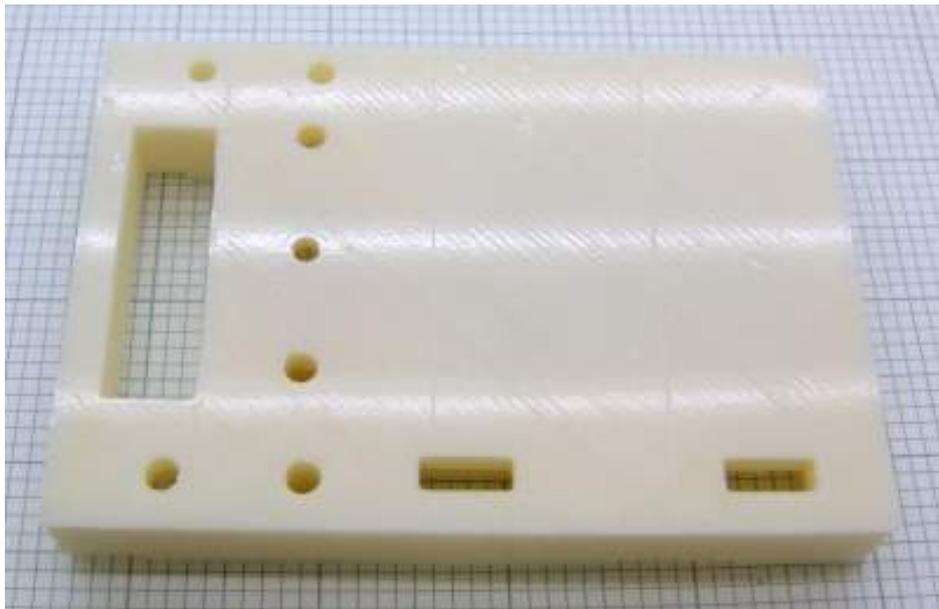
Somebody pointed out a while ago that you can get PET tape that is rated to 250°C. That is not as high as Kapton, but just about adequate for a heated bed when extruding ABS at 240°C.



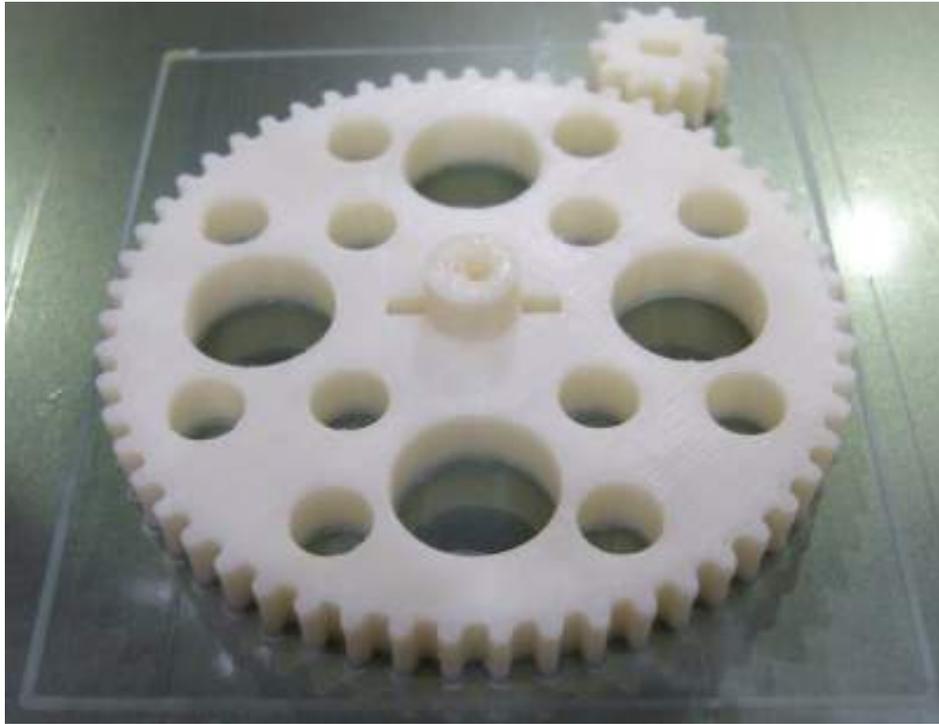
I bought some and when my Kapton stopped working I decided to give it a try. It seems to work well. The first layer goes down perfectly :-



and the objects stay flat: -



I do the first layer at 240°C with the bed at 120°C and subsequent layers at 220°C with the bed at 110°C. I have made all the parts for an extruder on it so far and it has performed perfectly. The extruder will be on eBay this evening.



It is too early to say if it better than Kapton, but it looks promising.

# Flash bang bed

Friday, 30th April 2010 by Nophead

As my MK3 heated bed on HydraRaptor has been working well I decided to scale it up for Mendel.

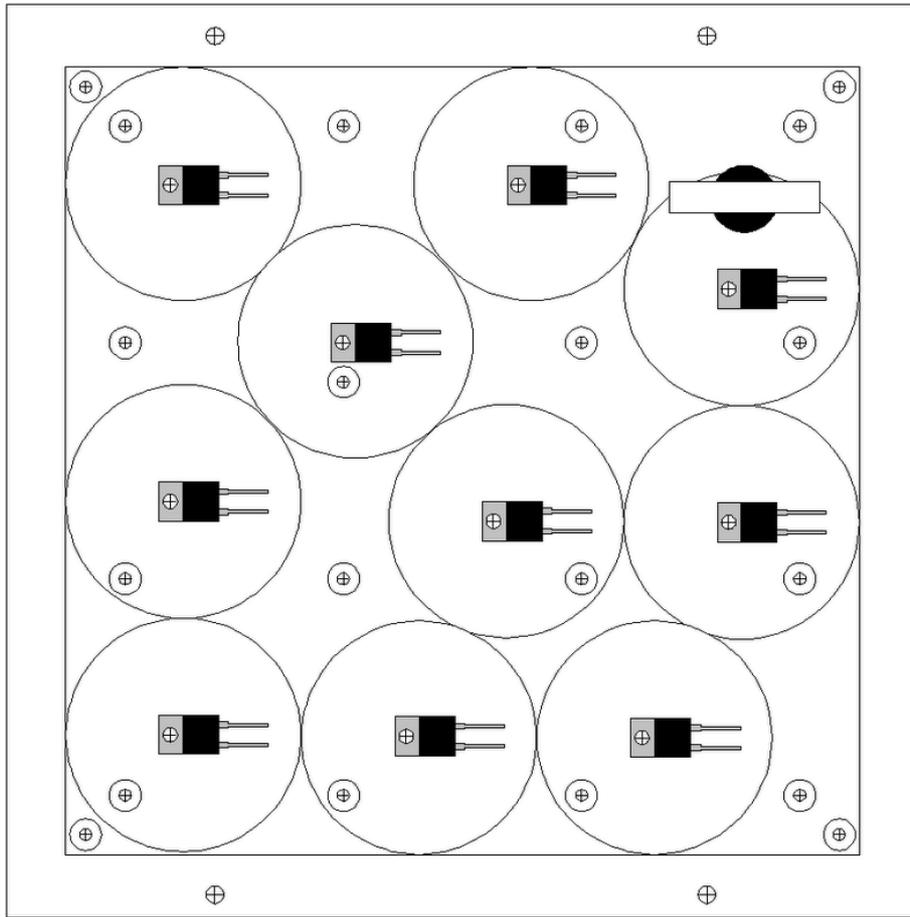
Buying aluminium that is flat seemed to be a hit and miss affair until a friend told me that what I need is tooling plate and put me in touch with a company that sells it. They recommended C250 cast machined tooling plate. It wasn't cheap (I got 5 pieces 200 200mm for ~ £140) but they are all flat.

I can't find a geometric definition of flatness. It is given as  $\pm 0.4\text{mm}$  for a 6mm sheet of C250 (I would have preferred 5mm to reduce the mass a bit but that is  $\pm 0.8\text{mm}$ ). I take it to mean that all the points on the surface of a metre square plate will lie in a volume 0.8mm high. For a 200mm piece I expect the deviation to be about 1/5 of that, i.e. 0.16mm assuming it is a single curve rather than wavy. Since the bed can be levelled at the corners the deviation in the middle should be about half that again, 0.08mm, just about acceptable for raft-less printing.

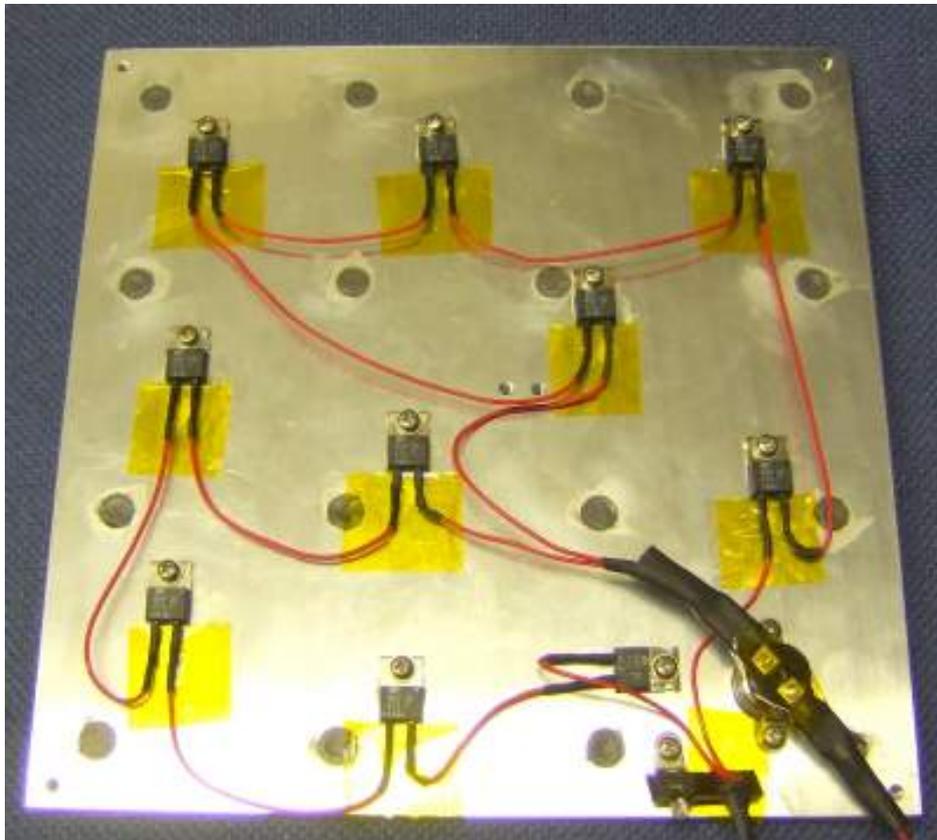
When I tried levelling the bed I ran into a problem though. With my Dibond bed I could level each corner because it can flex a bit. With the rigid aluminium bed I can only level three out of the four corners at a time. When I move the nozzle to each corner in turn it behaves as if two diagonally opposite corners are lower than the other two. That would imply the plate is not flat, but I know it is when I put a straight edge across it. I think this means that the two y-axis bars are not quite level with each other at both ends, causing the bed to twist about the y-axis as it traverses it. I expect it could be corrected by adjusting the frame but I haven't got my head around what to adjust and in what direction yet.

Given that I am using 188W on a 150mm bed on HydraRaptor, to get a similar warm up time I would need 335W. That seems a lot to get from a PSU, so I decided to make it mains driven. I found that I could get 47 TO220 resistors cheaper than other values. Five in series across the mains gives about 250W, so I used two strings of five to give 500W. That gives a warm up time of about three minutes.

Equally spacing four or nine resistors on a square is easy but placing ten is an interesting problem. I used the solution to packing ten circles in a square that I found here. This is my layout with 16 magnets as well.



And here it is wired up: -



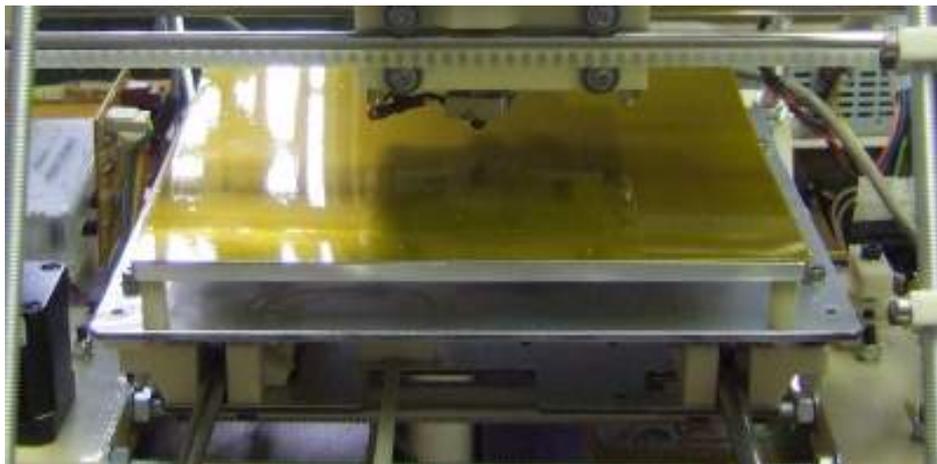
I used wire with PTFE insulation rated to 300°C. I have an earth connection of course. It would be a good idea to have a second earth in case the first one breaks due to the constant bed movement. I also fitted a 150°C thermal cut out that came out of a microwave oven. With 500W it would get very hot indeed if the control circuit failed.

I intended to mount the magnets the way I did before, by drilling holes not quite through, leaving a rim to retain them. I didn't tighten my drill stop enough and went all the way through so I decided to glue them in with JB-Weld.

I placed the bed onto a sheet of glass with some cling film on it. I then dropped in the magnets and glued them. When I turned it over the next day I found the magnets were sticking up from the surface. The glue must expand as it sets pushing the magnets down and lifting the plate!

I tapped them down with a punch but, unsurprisingly, they fell out the first time the bed was heated. In the end I jammed them in with PET tape. Drilling part way through is a much better solution.

I mounted the bed on top of the Dibond bed with nylon stand-offs.



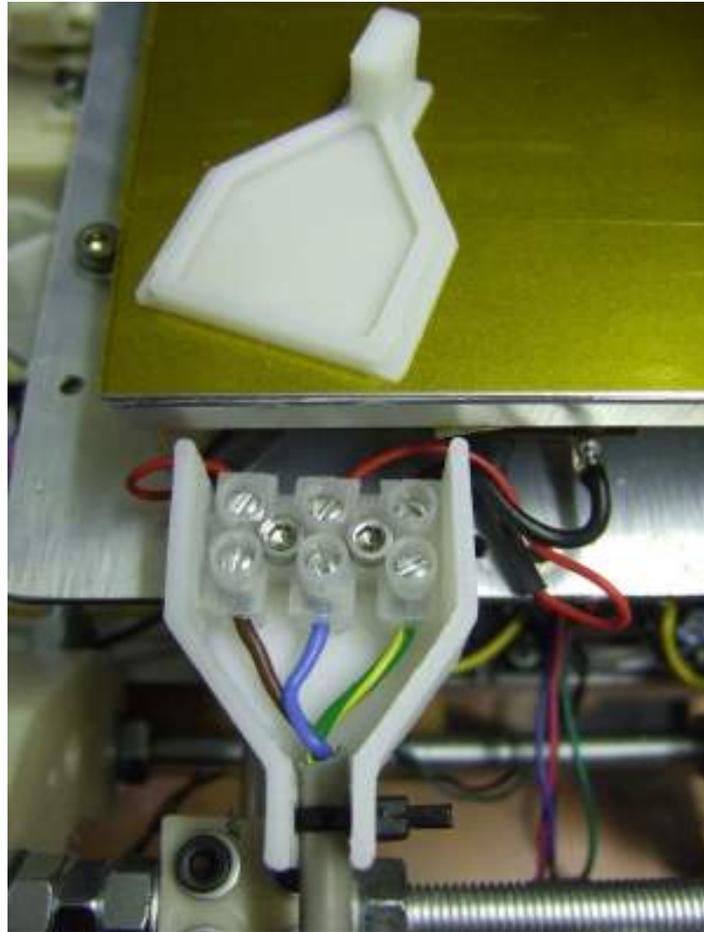
Not an ideal solution as a lot of z-travel is lost, but the thermal cut-out is quite deep.

I used chocolate block connectors to wire up the mains. To make them safe and provide strain relief for the cables I RepRapped some plastic covers.

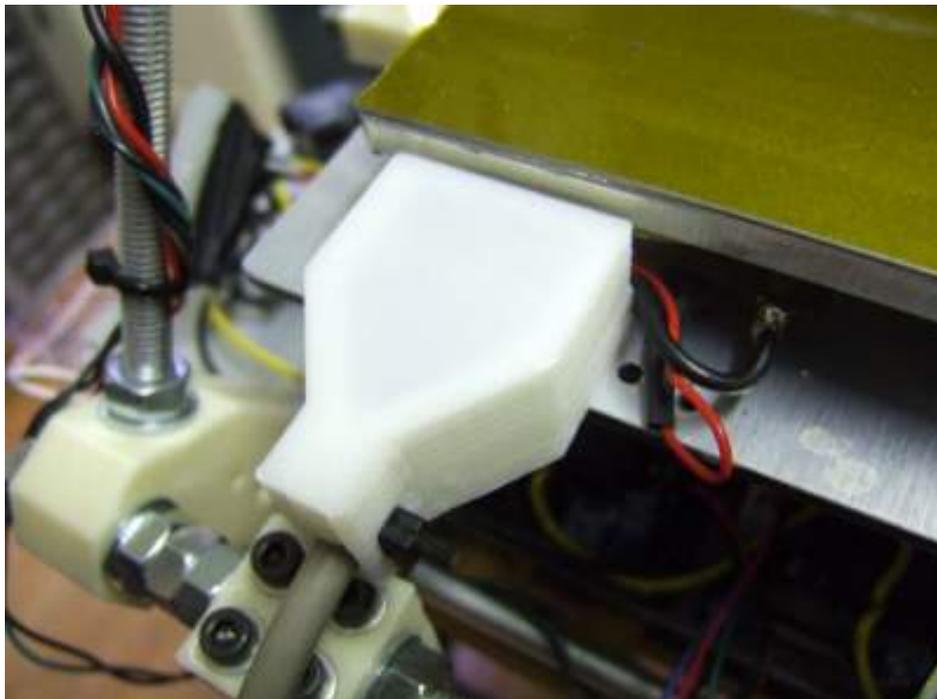


The lids just clip on with some tabs that fit into small slots. They didn't fit very tightly, I need to make the tabs bigger and a tighter fit. A boss and a screw hole would have been better I think.





For safety all the wires should be inside the cover as everything accessible should be double insulated. I will make it wider at my next attempt.



The bed worked well for the first few objects I made. Simple bang-bang control gave about 10°C

overshoot initially but settles down before the object build starts so does not really matter. One thing I have realised is that the nylon pillars expand about 0.1mm when they warm up so I give them some time to do that otherwise the first layer has varying height.

I got some new ABS from [reprapsource.com](http://reprapsource.com) that turned out to be white, I was expecting natural as that is easier to work with. It seems to need higher temperatures to get it to stick to itself and the bed. I am extruding at 240°C with the bed at 140°C for the first layer and 110°C after that. I built one object like that and then disaster struck. The bed heated to 140°C and levelled off. While the extruder was heating I heard a few pops and crackles. When I looked at the temperature graph I saw the bed temperature soaring. Before I had time to think what was happening there was a loud bang and flash from underneath the bed and the 5A fuse in the plug blew.

What happened was one of the resistors developed a short between its tab and one of the connections. That caused a path to earth which increased the power on the remaining four in the chain. Several of those went short circuit as well in a chain reaction which ended up shorting the mains. What I couldn't explain at first was why the firmware did not turn it off and why the thermal cut-out did not cut the power. It turns out that I had swapped the live and neutral connections in the IEC connector, which meant that the solid state relay and the cut-out were in the neutral connection. As soon as the first resistor shorted it had bypassed all the control, not good!

I had originally chosen the resistors when I was making a bed for PLA at 60°C. Looking at the datasheet they have a maximum operating temperature of 155°C but they are de-rated to zero wattage at that temperature, so by putting 50W into them at 140°C I am grossly over loading them. I have abused AL clad and vitreous enamel resistors in this way and not had any problems but the TO220 seem far less robust. I don't know what they use for the tab insulation but I wouldn't be surprised if it was epoxy. The high voltage may also have been a factor as the ones on HydraRaptor have survived a similar overload so far. They have the same de-rating curve, but are made by a different company.

I rebuilt the bed and changed my firmware to stay inside the power curve by reducing the PWM ratio as the temperature increases. Unfortunately, I found I could only get to 130°C so I had to change the zero power point to 200°C to get to 140°C in a reasonable time. Even then it takes 400 seconds instead of 175.

So far it is holding up, but it is nowhere near as fast as I wanted. A shame because I had bought 50 of the 47 resistors, but I think I will have to scrap them and go back to AL clad. The smallest ones that I have used before are not rated for mains voltage so I will need some bigger ones. PCB or stick on silicone heaters are starting to look more attractive!

# Plumbstruder

Monday, 3rd May 2010 by Nophead

Brian Reifsnyder asked for volunteers to test his hybrid PEEK and PTFE insulator design, so I used it for the hot part of my Mendel extruder to start with. The drive mechanism is Wade's design.



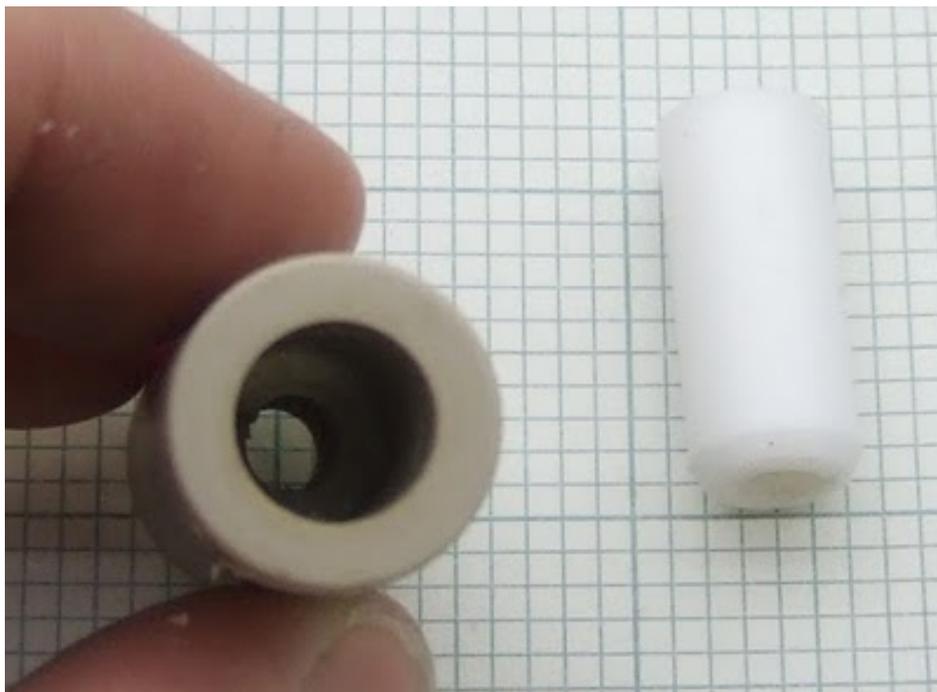
It worked well at first, requiring little force to extrude PLA, but got harder and harder until eventually it completely jammed. This video below shows that even with the nozzle removed and starting with a completely empty barrel I couldn't push more than about 15mm of filament through it.

The reason was that the PTFE liner had slipped a little leaving a small gap between it and the end of the brass heater barrel.



This makes the extruder jam completely solid. The reason is that PLA goes rubbery above 50°C, so any pressure on it makes it expand width wise and grip the side of the tube. If there is a gap that it can expand into it locks the filament.

I stripped it down, cleaned it out and reassembled it with some washers to hold the PTFE down.



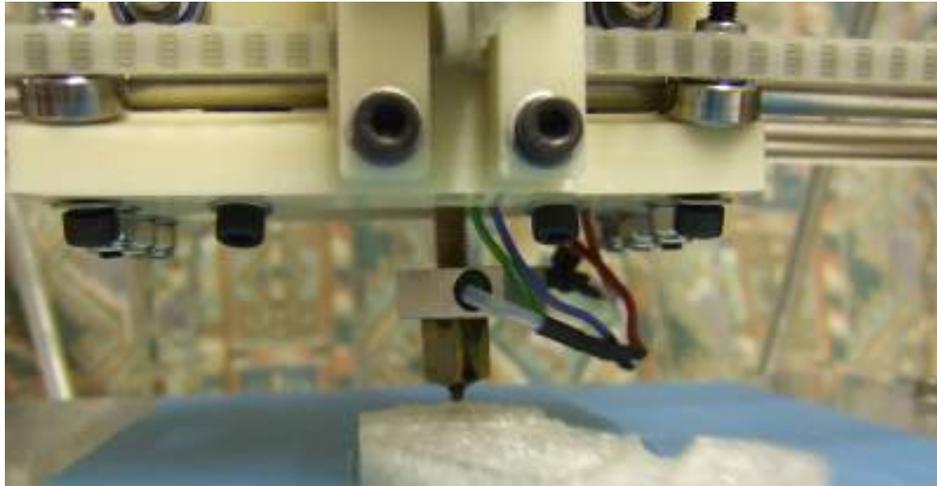
Brian has added a circlip to the design to solve the problem.



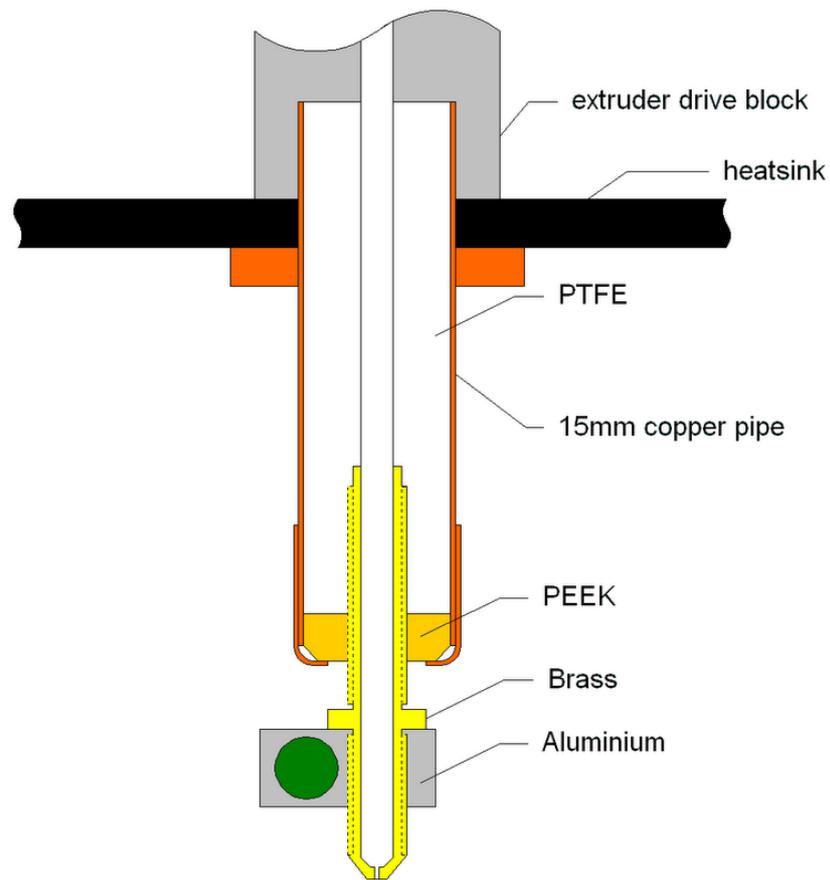
I haven't tested this version yet because I ran into another problem before it arrived. When I started using a heated bed for PLA the extruder jammed again. This time it was because the top end of the insulator got hotter than the glass transition of the PLA, so it swelled as it went into the insulator and jammed in the tapered entrance. There was also some leakage around the threads.



The reason it got too hot is a combination of the heated bed, the fact that I used an uninsulated heater with a large surface area, and the fact that the Mendel carriage traps the rising heat.

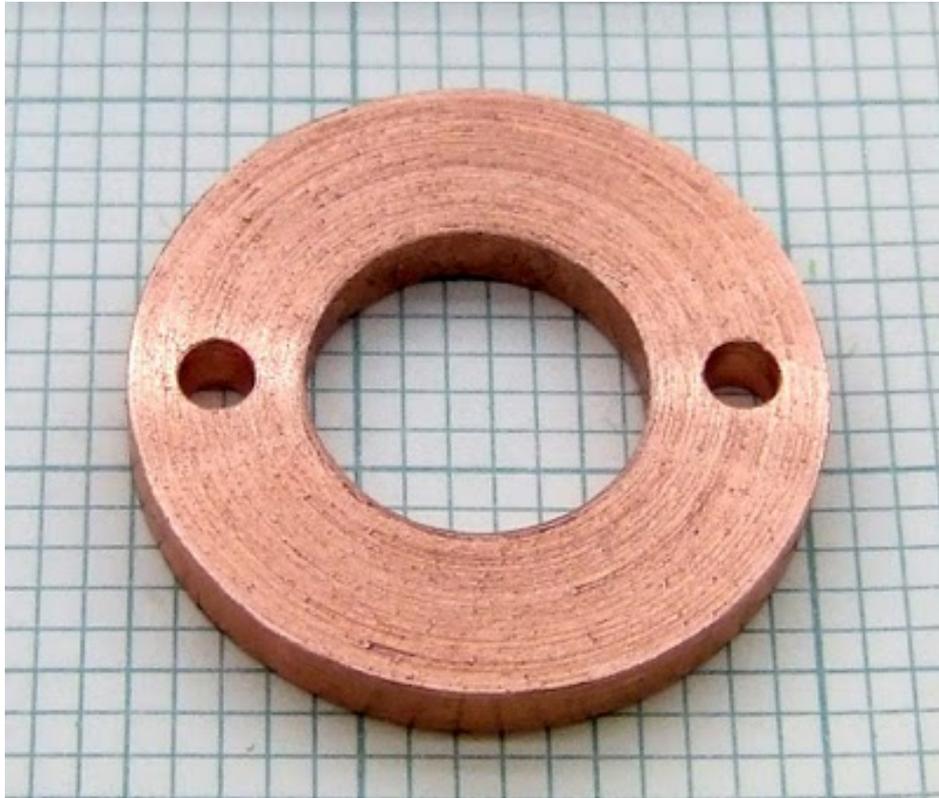


I decided to try out an idea I had a while ago, which is similar in intent to Brian's scheme. Instead of putting PTFE inside PEEK to stop it expanding I put it inside a 15mm copper pipe. This not only totally constrains it so it cannot swell, it also removes heat from it, shortening the transition zone. I am calling this one Plumbstruder. Here is a sketch of the layout: -



The end of the copper pipe is closed off by soldering an end cap on and then drilling it out to leave a lip to support a PEEK disk which the barrel screws into as well as into the PTFE. That means the PEEK supports the extrusion force, as in Brian's design, but I also use the thread in the PTFE as a seal rather than just having a compression joint.

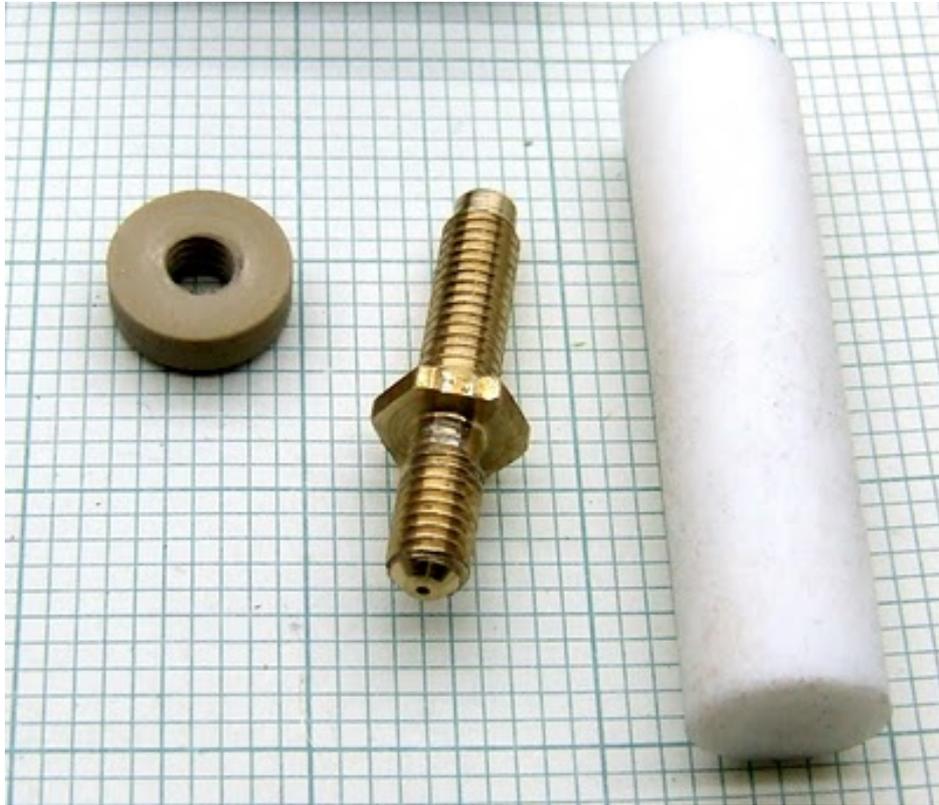
The copper pipe gets hot so I coupled it to a big heatsink with a copper flange.



I turned this from a solid block of copper a friend gave me (thanks Paul). I soldered it onto the pipe and screwed it onto the heatsink.

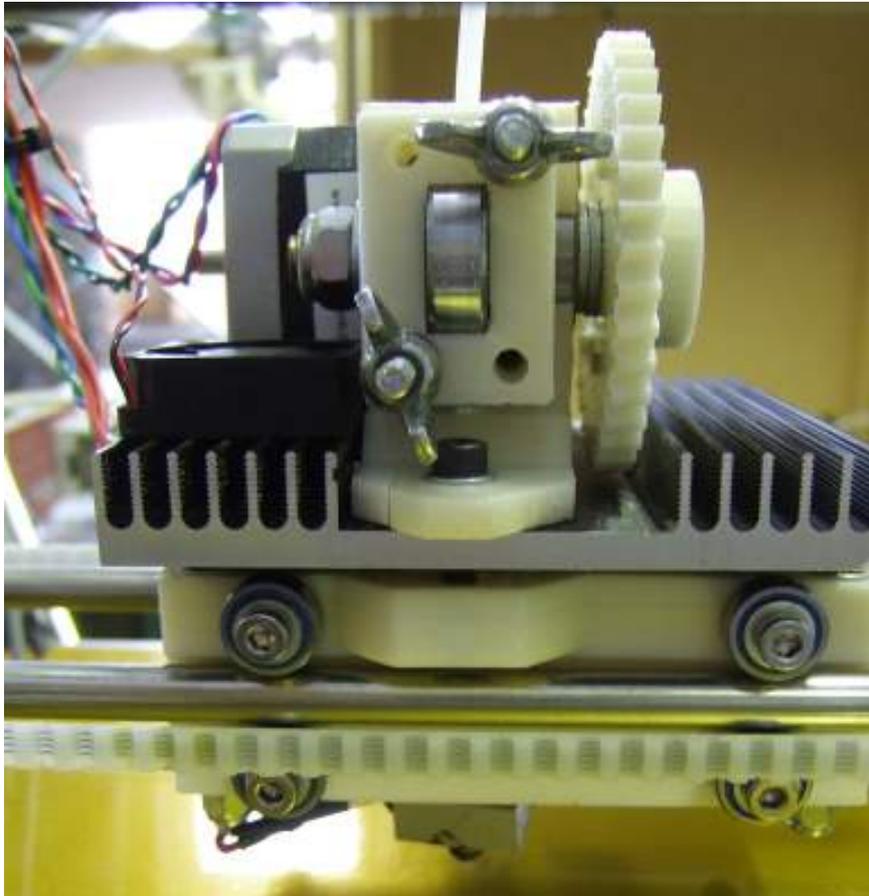


I turned the one piece nozzle / barrel from hex stock so it has a nut shaped flange in the middle to make it easy to screw in and also gives the aluminium heater block something to tighten against.



I had to turn down the PTFE to be a tight fit inside the pipe. I was hoping to find a size where the ID of the pipe matched the OD of the PTFE. 22mm copper pipe has an ID of 20mm, so theoretically 20mm PTFE rod would fit. In practice I have found that PTFE rod is about +/- 0.5mm so, unless you were lucky, the fit would not be good enough.

Even with a big heatsink it was getting uncomfortably warm so I added a tiny fan.



I have been using this extruder on my Mendel for a few weeks and it is totally reliable, with no sign of leaking. I think that of all the extruders I have made, this one needs the least force to extrude. I can push plastic through by hand at high speed with ease. For an extruder to work I think the transition zone needs at least two of the following three attributes: short, slippery or tapered. Unfortunately a short transition zone seems to mean using a heatsink, which is not ideal for a moving head machine.

I also think a short melt zone improves the accuracy by reducing the start-stop time. In that respect this design is not ideal, although it is no worse than the standard design.

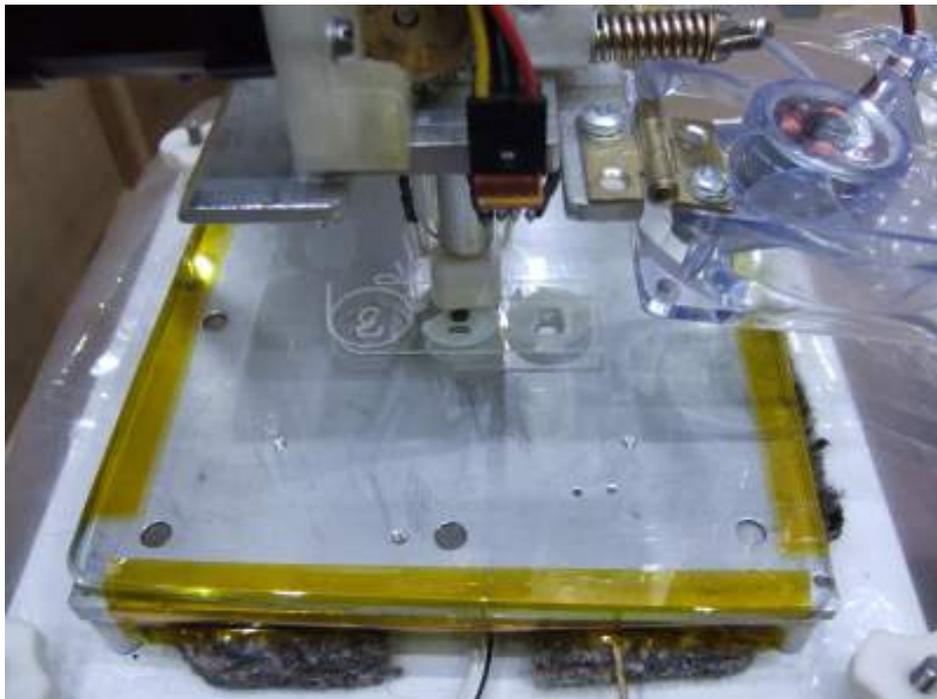
# PLA on glass

Friday, 14th May 2010 by Nophead

A while ago Jordan Miller emailed me to say that PLA can be printed on hot glass. He had tried ABS but it did not stick at 90°C, which was the highest temperature his bed would go so I said I would try it at 140°C.

I found a piece of glass the same size as HydraRaptor's bed that was 5mm thick. It used to be the platform of a kitchen weighing scale. It has nice rounded corners, the only problem was that it had an aluminium boss glued to it. I tried to remove it first with a hammer, then I tried acetone and finally I tried a hot air gun. None of these methods worked so I put it in the oven at gas mark 6 for 10 minutes. It then just lifted off with a pair of tongs.

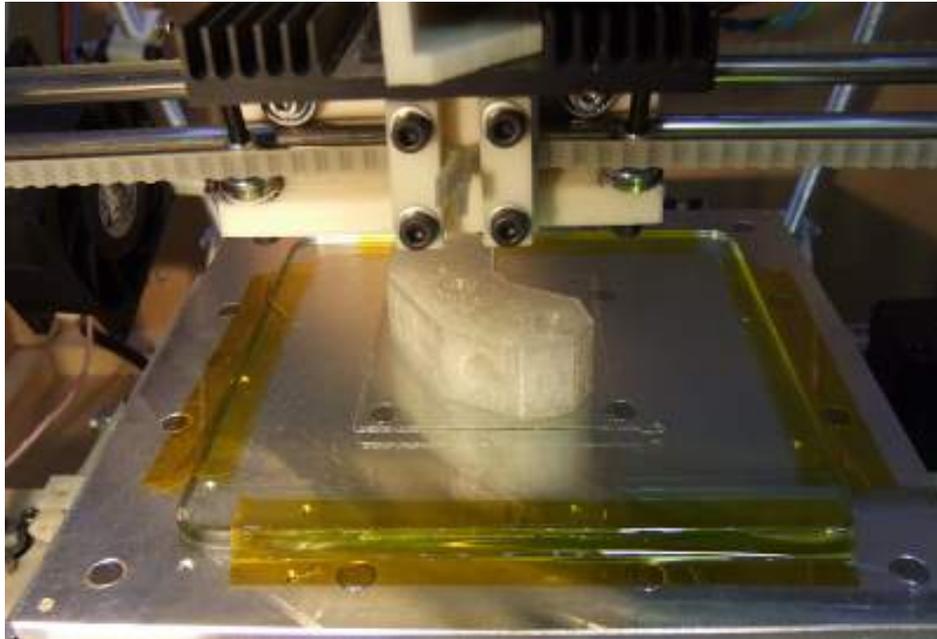
For a quick test I just taped it down with some Kapton tape. It holds firm as long as you do all four sides.



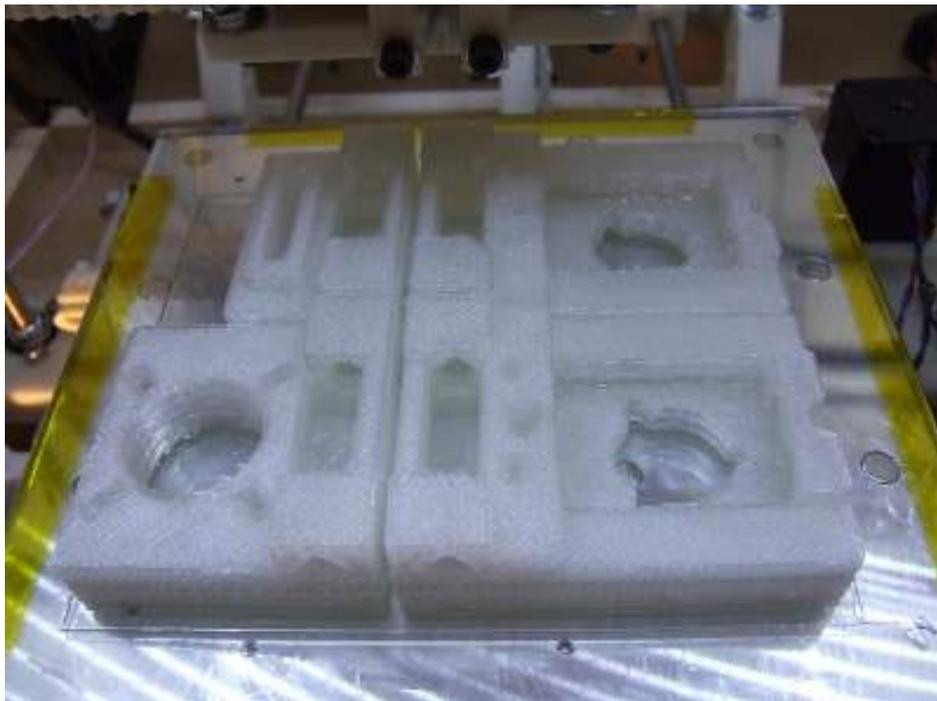
As you can see ABS does not stick to glass at 140°C.

Next I moved the glass onto my Mendel as it was set up for PLA at the time and I couldn't get PLA to stick to PET tape.

I printed a frame vertex on glass with the bed starting at 120°C for the first layer, dropping down to 45°C for the rest of the build.



That stuck well but came off easily when the bed was cooled. Next I tried a new piece of 4mm glass cut to the size of the bed.



That stuck so well that it took several blows with a hammer to to remove each object. One piece chipped when it hit the wall behind! For some reason the new glass seems to stick much better than the old.

The objects come off perfectly flat and glassy.



I dropped the bed temperature to 100°C, which makes them a little easier to remove, just a sharp tap with a hammer rather than a heavy blow! Any lower than that and I have trouble getting the outlines to stick. Jordan uses only 65°C and reports the objects are easy to remove, so I am not sure what I am doing wrong, different PLA perhaps. If I start with the head lower then the plastic rucks up during the first layer infill.

So glass looks like a good bed material for PLA as it comes completely flat and hopefully should not degrade. Jordan reports that finger prints prevent objects sticking but they can be removed with alcohol. Copper clad PCB material has the advantage that you can flex it to remove objects but doesn't give as good a finish.

# Black and White

Monday, 24th May 2010 by Nophead

I bought some new ABS filament from [reprapsource.com](http://reprapsource.com) as it is a reasonable price, the postage from Germany is not too bad and being in the EU there are no customs charges, so it does not get held to ransom by Parcel Force for their ridiculous handling charge.

The advert does not state a colour so I assumed it would be natural, however when it came it wasn't like any ABS I had encountered before. Natural ABS is cream coloured and opaque. This was white and a bit translucent. At first I thought it was HDPE, but when bent it bruised, which is a characteristic of ABS.

I ran it first in HydraRaptor. The only issue I had was that it didn't want to stick to the PET tape I was using until I raised the bed temperature to 140°C for the first layer and extruded at 250°C. For subsequent layers I revert to the bed at 110°C and filament at 240°C.

The objects produced look nice in white and seem to be harder than those made in natural. I don't think it is simply pigmented ABS, I think it is a different formulation.

My impressions of using PET tape instead of Kapton tape is that it doesn't seem to give as much grip as new Kapton, but it doesn't degrade. I can make most things on it with HydraRaptor without any warping at all, but Mendel bed springs tend to come unstuck. This is because they are relatively tall and have very little contact area with the bed. If the extruder hits a slight blob on a high layer it will snap the part off. Sometimes the loose part hits another part and starts a chain reaction where they all fall off.

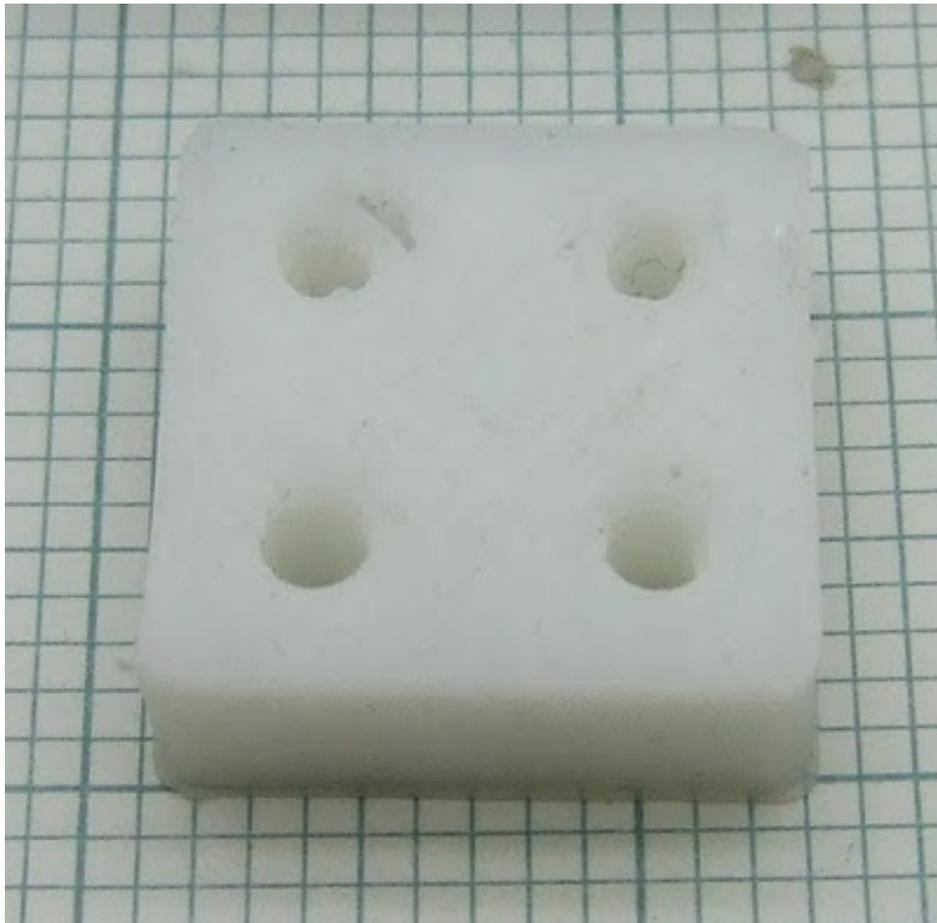
When doing raft-less builds on PET or Kapton it is essential that the first layer outline sticks perfectly and has no gaps in it, especially at the corners. If the first layer is too high it obviously doesn't stick and takes short cuts across the corners. If it is too low it also lifts at the corners though. What happens is that the filament becomes squashed into a flat ribbon. When that tries to bend around a sharp corner the outside has to stretch but instead it lifts and folds over inwards. A difference in z-value of 0.05mm can make all the difference. Increasing the temperature also helps to make the plastic bend around corners. If a corner does not stick perfectly then after two or three layers it will curl up at an angle of about 45°. This effect is not like the corner warping you get on a cold bed. It is much more localised and extreme. Small objects tend to come off during the build if a corner lifts.

With the natural ABS I was using before on Kapton it was far less critical. Objects stuck so well I had to remove them with a hammer or use a flexible bed. With white ABS on PET tape the objects can be removed more easily. Sometimes they just come free when they are cooled.

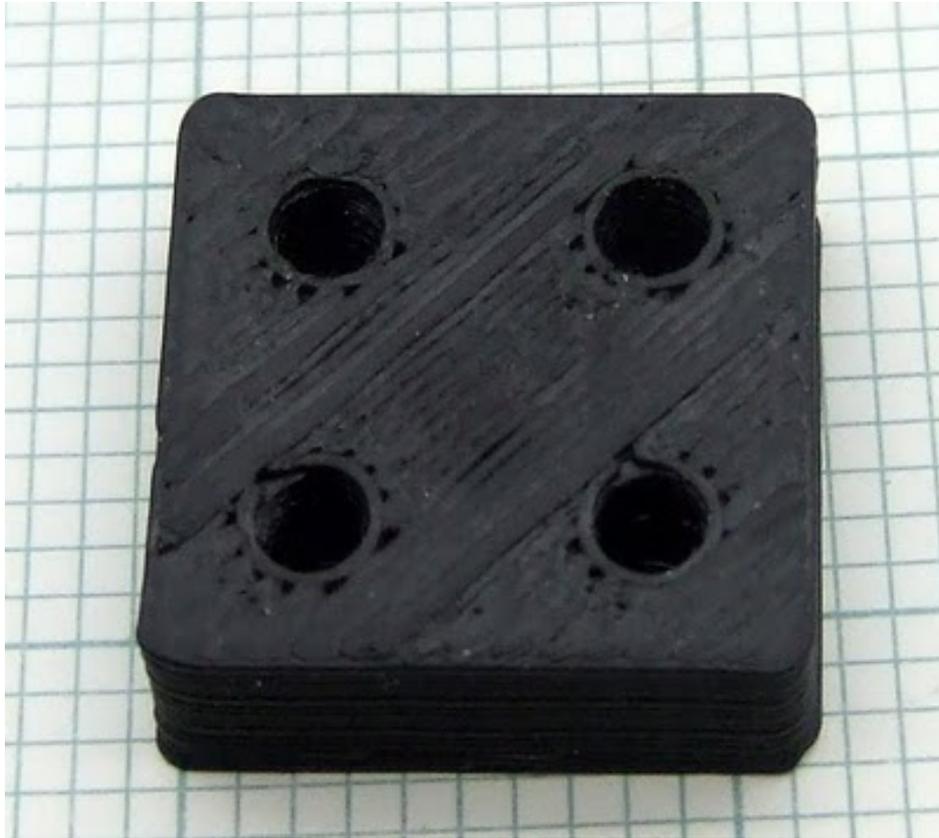
When I tried the new ABS in my Mendel it took a lot more tweaking to get it to work. The first issue

was that I had to increase the feed rate by about 18% relative to what I was using for PLA. My theory is that being softer it presses further into the threaded pulley and so sees a smaller pulley diameter. The hobbled M8 bolt has an internal radius of only about 5mm. The drive pulley on HydraRaptor is about twice that diameter and seems give more grip on softer plastics and doesn't need the 18% bodge factor when switching from PLA to ABS. I just tell it the filament diameter and it just works.

The next problem I had was that holes tended to shrink inwards and not meet the infill as you can see on this piece.

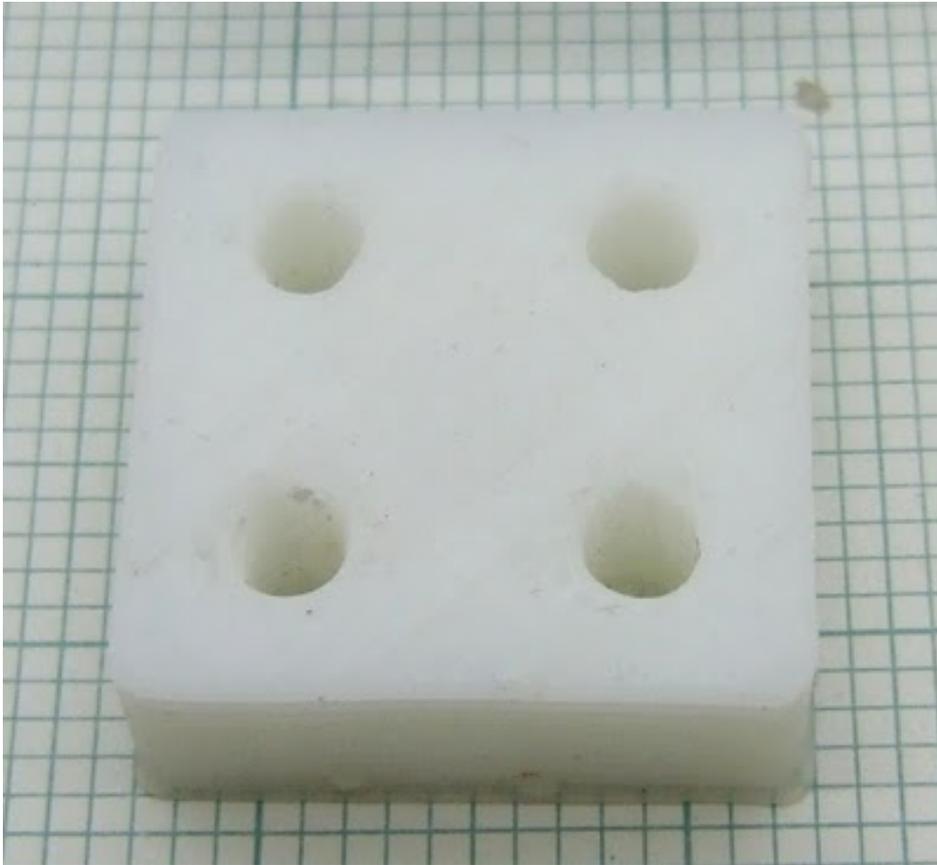


I also find PLA has a tendency to do this on my Mendel but not on HydraRaptor. For a sanity check I built the same object from the same g-code with black ABS.

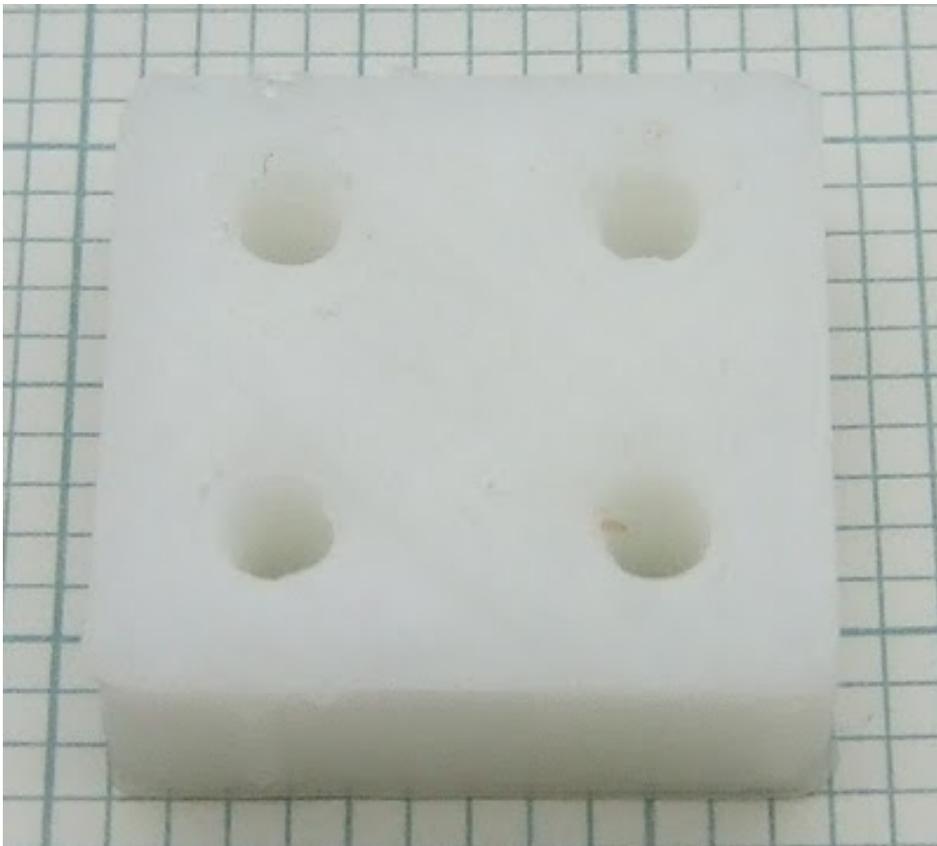


Notice how much bigger the holes are.

When I was flushing the black out again with the white I noticed that the white had far more die swell and was coming out at about 0.7mm. The black was only about 0.55mm. This means that to extrude at 0.5mm the white is being stretched a lot more, which accounts for why the holes shrink inwards. To test this hypothesis I ran the same g-code again scaling up all the coordinates by 0.6/0.5. This produced a bigger object but the holes are much better.



I then re-sliced the object for 0.6mm filament and that also printed correctly.



So it seems that the white ABS has more die swell than natural or black. In that respect it also

reminds me of HDPE. For some reason HydraRaptor is not affected and seems to have less die swell despite having a smaller nozzle, which normally gives more die swell in relative terms because the pressure is higher.

The other thing I discovered is that black ABS does not stick well to PET. It seems a bit greasy. So with a 0.5mm nozzle I have to build objects at 0.6mm when using white ABS in my Mendel, but with a 0.4mm nozzle on HydraRaptor I can build at 0.375mm or 0.4375mm no problem and holes do not shrink excessively. I am not sure what the difference is, perhaps the length of the nozzle aperture.

# Wooden overcoat

Saturday, 12th June 2010 by Nophead

I can make raft-less ABS objects on a heated bed pretty reliably, but when I try to do a whole bed full I get corners lifting on the objects near the edge of the bed. I think the reason is that the air around them is not as hot. If you think about it, with a moving bed machine like HydraRaptor, if you have a single object in the centre of the bed then you have a buffer of hot air around it. The bed only has to move by the dimensions of the object, so if the object is less than half the size of the bed then it remains inside that buffer. When you make objects near the edge of the bed the buffer is smaller and the bed moves further, so you get a double effect. To mitigate this effect I have halved the size of my biggest build trays. This is less convenient as a full bed is about 8 hours giving three shifts a day.

For example, with natural ABS on Kapton I was able to get away with a full bed like this: -

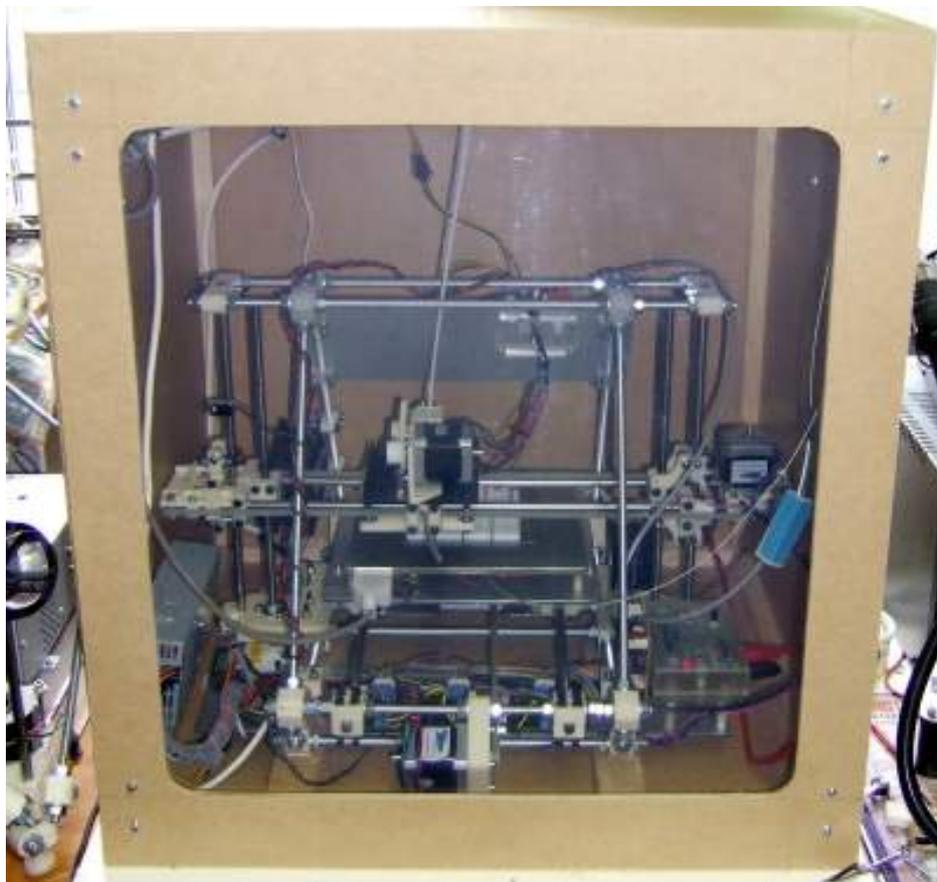


... but with white ABS on PET tape I would always get the odd part around the edge lifting, so I have to do it as two builds now. I bought a new reel of natural ABS from MakerBot but I can't make it work with HydraRaptor. I made a couple of objects but then it started to always jam after a few layers. The reason seems to be that because it is undersized at about 2.8mm, and my barrel has an internal diameter of 3.6mm, molten plastic back-flows up the barrel as far as the cold zone, where it freezes and makes the filament hard to push. This causes the filament to buckle and jam. I don't understand what has changed. The last reel I got from MakerBot a long time ago was the same diameter and I only finished using it recently and had no problems in the same extruder with the same settings. I switched back to white ABS and it works reliably again, so it must be something to do with the plastic.

Another problem with ABS is the fumes. My Mendel extruder seems to give off more fumes than

HydraRaptor's does, perhaps because the melt zone is much bigger, and the white ABS seems to smell more acrid than natural ABS. I did a build with a window open to get rid of the fumes but most of the parts then warped, presumably because there was no longer a buffer of warm air around them, but a cool breeze.

In an attempt to tackle both of these problems I built an MDF box around my Mendel.

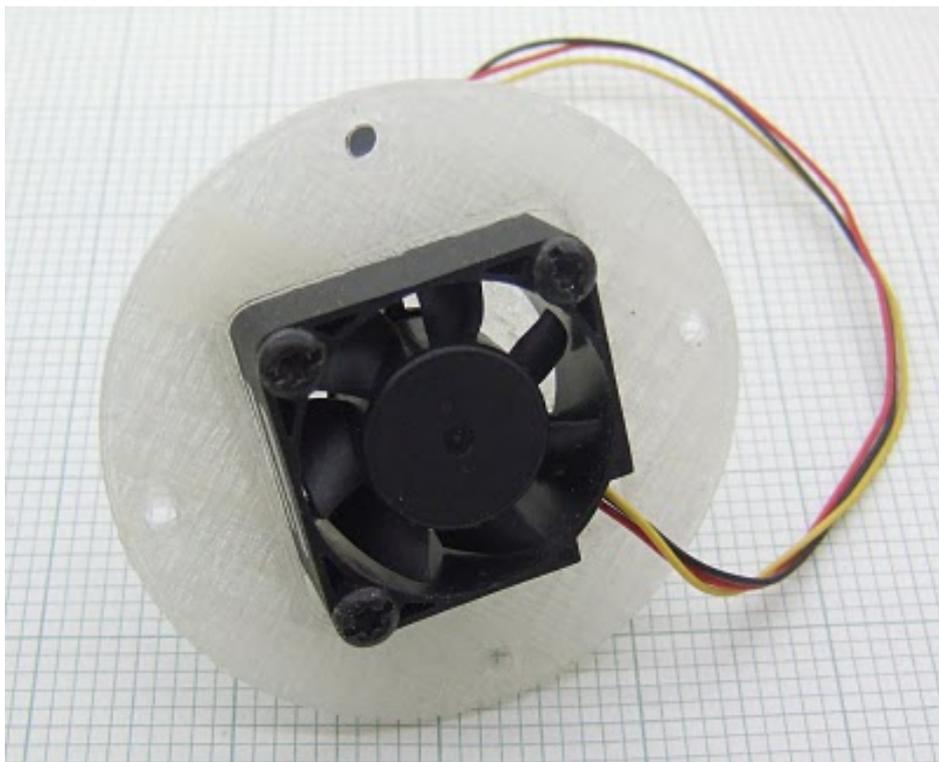


The front of the box is held on by magnetic door catches. It is sealed by door draft extruder strips and has a window made from plastic from a picture frame. This is glued on with silicone sealant.

The box is tall enough to allow the filament to enter through a single hole in the middle of the roof with a felt gasket that catches the dust.



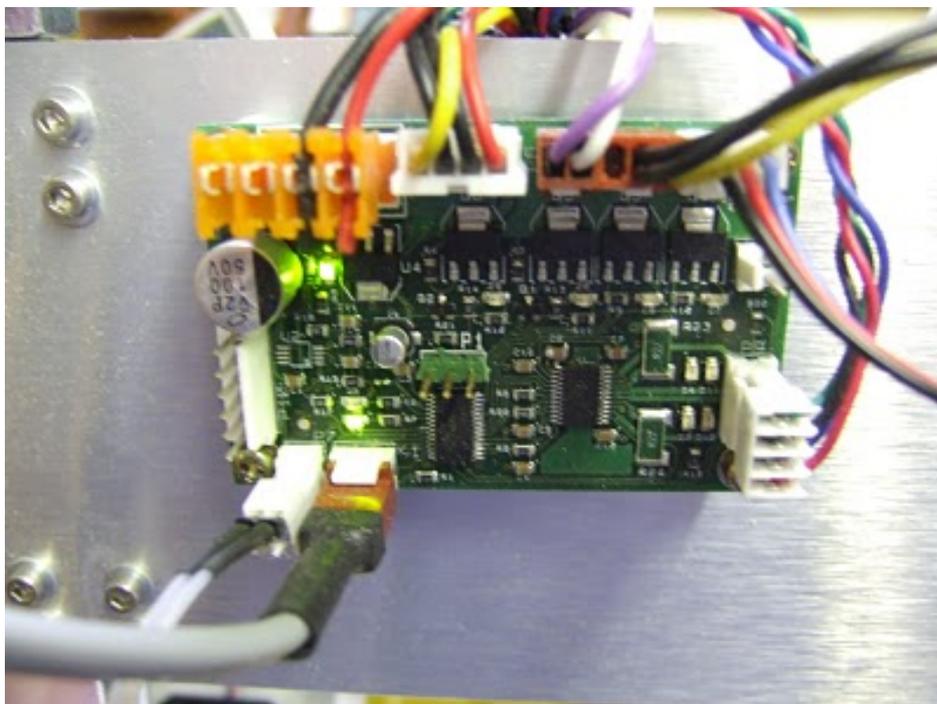
The fumes are extracted by a tiny fan mounted in a chimney in the roof and piped out through a window vent.





I made a little pipe with a flange that fits into a slot in the vent and taped up the other slots with PET tape. I have another vent in the other window for fresh air in.

This fan is controlled by a spare output on my extruder controller and I have a thermistor to sense the air temperature in the middle of the chamber at the height of the top of the Mendel frame. Together with a small fan to cool the extruder heatsink and a large fan to cool the bed that uses up all the free outputs of my extruder controller, but not for the uses I originally envisaged.



I set the target chamber temperature to 40°C because that is as high as I dare to run the electronics and power supply. With the front closed the small fan cannot hold the temperature down and I have seen it go as high as 50°C without any ill effects. The extruder stepper was then too hot to touch though. Note there is no chamber heater. All the heat comes from the uninsulated bed, extruder and the motors and electronics, so I have actually reduced the total power

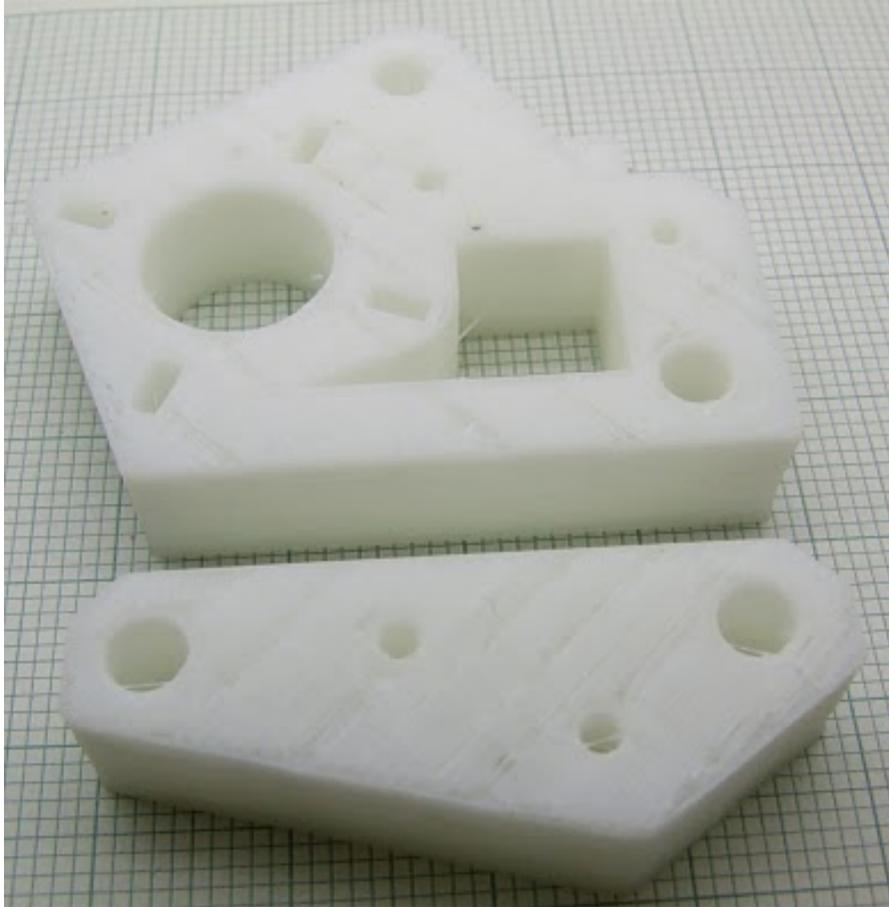
consumption slightly and gained a heated chamber. To maintain 40°C I have to leave the front open at the bottom. I will add some vents at the bottom of the sides to allow cool air in and perhaps use a bigger fan.

Even with a gap at the bottom of the door I cannot smell any fumes. Since using the chamber nothing has warped provided the first layer outline went down properly as discussed in my last post. It also makes the machine very quiet although it was already much quieter than HydraRaptor.

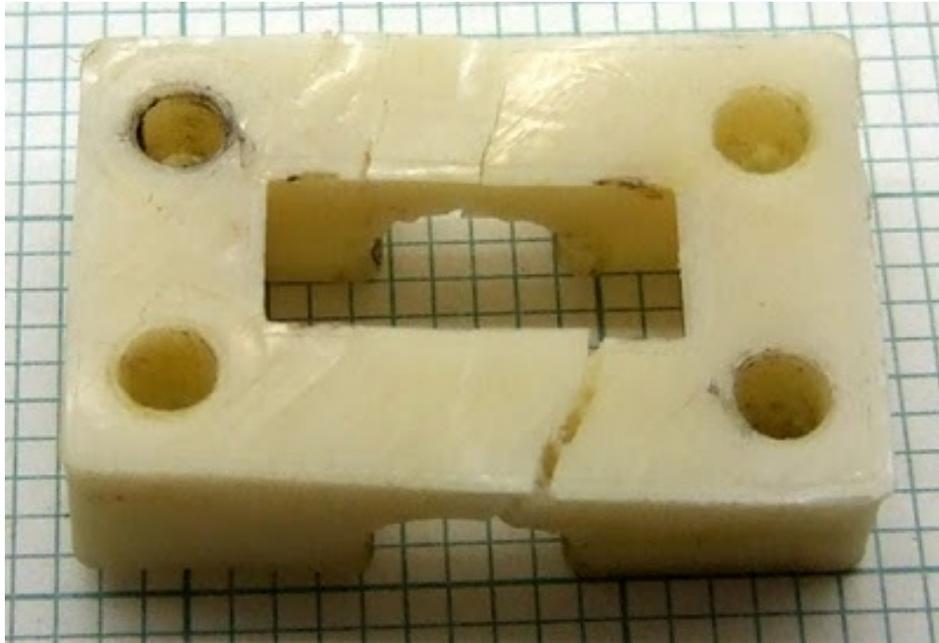
# Broken bracket breakdown

Thursday, 1st July 2010 by Nophead

Whilst printing a 16th set of Mendel parts, my Mendel printed a bed of brackets with bits missing: -

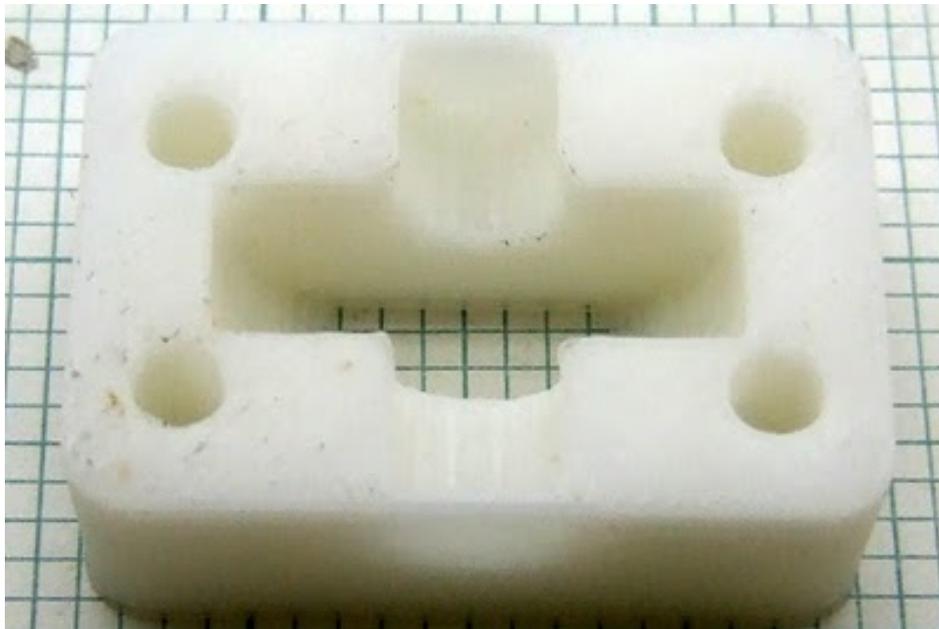


On investigation I found the idler bracket on the extruder had broken, so there wasn't any pressure on the pinch wheel.



It lasted a long time before it broke but clearly it wasn't strong enough. Wade made his in PLA, which is harder and I only use two of the four bolt holes, so mine is under more strain.

I made a stronger replacement. It is thicker and a little bit bigger in the other two dimensions. I also made the holes 4.5mm rather than 4mm so it slides on the bolts easier and I capped the ends of the axle holder as mine tended to slide sideways.



The files are on Thingiverse.

# ABS on PC

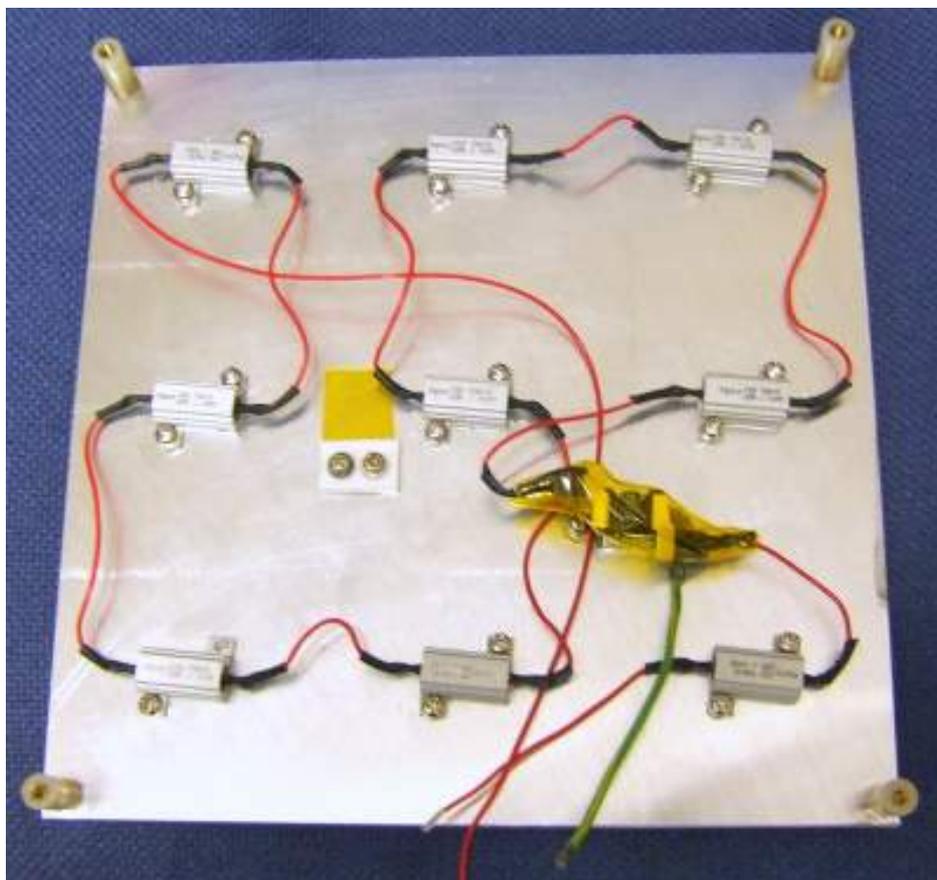
Saturday, 3rd July 2010 by Nophead

My last heated bed ran for a long time but it finally went pop on Mendel print number 15. The TO220 resistors developed a short to earth about half way through an 8 hour overnight build. It took out a 5 Amp mains fuse and destroyed the 4 Amp solid state relay that was controlling it.

Clearly the cheap TO220 resistors are just not suitable for abusing as heating elements, so I went back to using aluminium clad resistors. The disadvantage is that they are higher profile and need two accurately drilled mounting holes, but they are a lot more robust and cheaper. The more expensive TO220 resistors I used on HydraRaptor are still going strong, but there is nothing to suggest that they are any better in their spec. It is the tab insulation that breaks down though, so it could be just the fact that the voltage is much lower on HydraRaptor.

I have used the Tyco THS10 series at temperatures up to 240°C and not had any fail yet. They are not rated for mains voltage though, so I moved up to THS15 series which are. They are slightly taller, which doesn't actually matter because I use 20mm stand-offs, so there is still sufficient gap. The mounting holes will take an M2.5 screw, but I didn't have any to hand, so I drilled them out for M3. There is just enough room for a screw head with an integral washer, a standard washer would not fit.

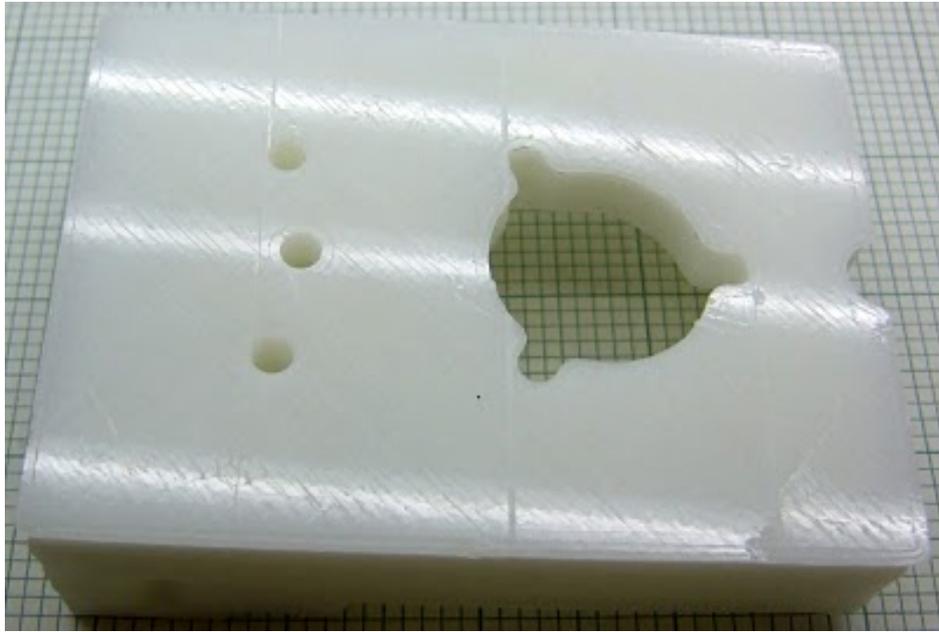
I have run the THS10 at about twice their rating so I did the same with these: 9 22 in series gives a total power of 290W at 240V. That gives a warm-up time of about 4 minutes to 140°C. My extruder takes longer to get to 255°C, so I set them both off together so that the bed has enough time at its steady state temperature for the nylon pillars to expand fully.



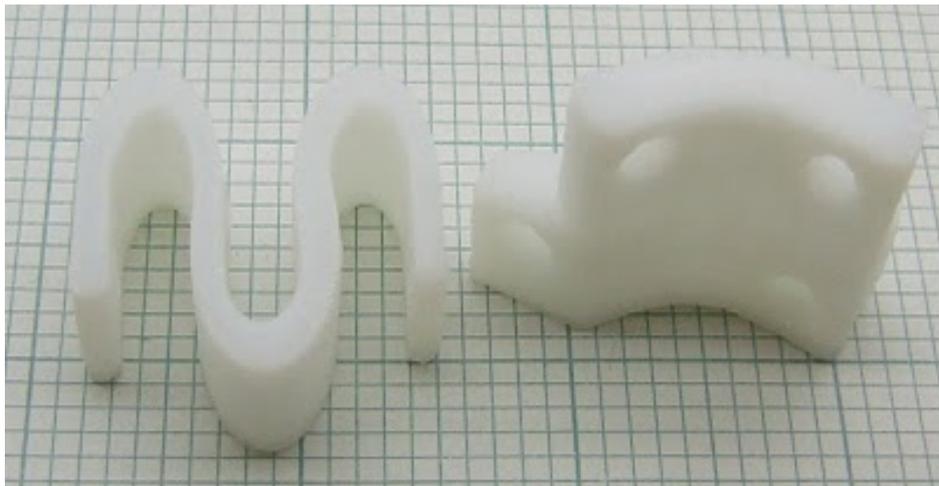
The white PTFE clamp is where I attach the thermocouple. The device wrapped in Kapton tape is a 190°C thermal cut-out to prevent melt down if the firmware crashes or the solid state relay goes short circuit. The mains wire has PTFE insulation to handle the temperature. Since the wiring is exposed it should really have an extra layer of insulation to be considered safe, but I am not about to stick my fingers under a hot bed so I didn't bother. If you have children or animals, or are completely risk averse, then you probably should.

I haven't put any magnets on this one yet as I haven't been making use of the ones on the last bed since I started using white ABS on PET tape. The objects mainly come loose when they cool down and are easily removed without having to remove the steel plate and bend it.

ABS on PET tape works well. The grip level seems to degrade much more slowly than Kapton does. After lots of use it becomes easier to remove objects, but then the amount of grip is not quite enough for some parts. I can make most of the Mendel parts time after time, but I have problems with a few. The outer corners lift slightly towards the end of the build of the large Z brackets when the PET is old and I am building more than one at a time.



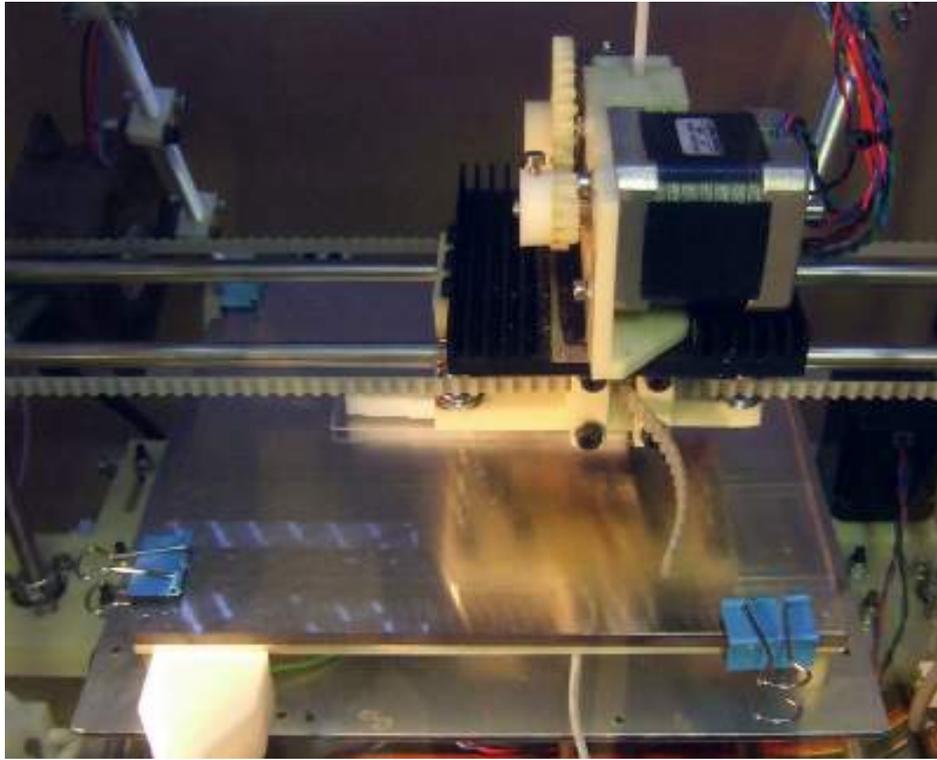
Not easy to see, but the bottom right corner has lifted by about 0.5mm. It makes no difference to the function of the part but I like to get them completely flat.



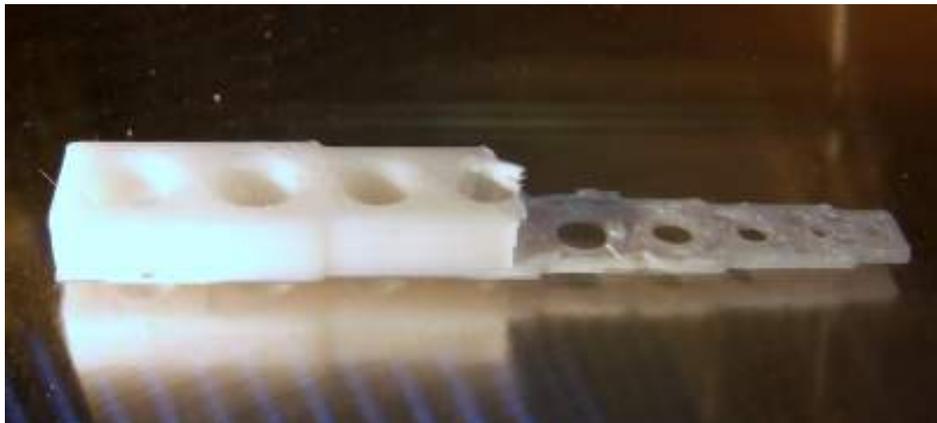
At the opposite end of the scale I have problems with the bed springs and the X 360 Z bearing plates. These are very tall compared to their footprint, so as the nozzle bushes past the top of the objects they often ping off the bed due to the small contact area and the high leverage. When the PET is old I have about a 30% reject rate with these unless I do them one at a time.

I had a 5mm sheet of polycarbonate that I have been meaning to try as a bed material for some time. I think that is what is used on commercial machines. It has a high melting point (267°C), so will not melt when the hot filament lands on it. It also has a high glass transitions (150°C) so shouldn't soften on a heated bed.

I clamped it to the aluminium bed with some bulldog clips.



I tried it cold to start with but the ABS did not stick so I tried it at 140°C next. I made a test shape that I am using to research hole shrinkage. It stuck so well I broke it trying to get it off.



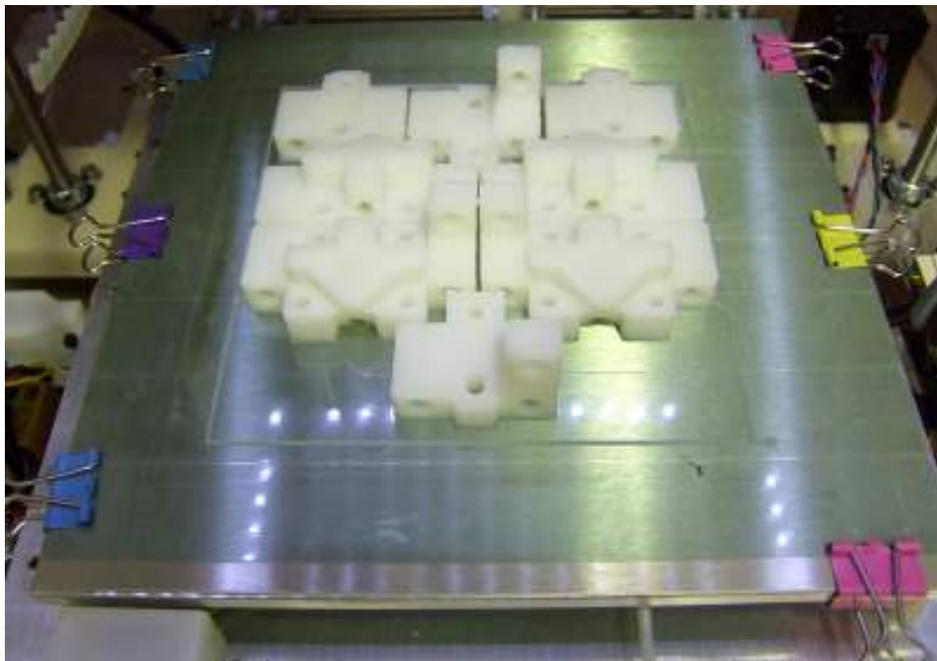
I had to use a chisel to get the rest off. Strangely, although the ABS is extruded below the melt point of the PC, so it can't form a diffusion weld, it forms a stronger bond with the PC than to itself.

I dropped the initial bed temperature to 50°C which seemed to be the lowest I could get the first layer outline to stick properly. After the first layer I set the bed temperature to 90°C to reduce the warping stress in the ABS. These are temperatures on the underside of the aluminium, so the top surface of the PC will be something like 15-20°C lower.



I made these tall objects that tend to come unstuck from PET. These held well, in fact, when I removed them, most of the springs and one of the bearing plates left their bottom layer behind. Not really a big problem, the bottom layer becomes a minimalist raft!

For general production I went back to PET tape. I covered a sheet of 1.5mm thick stainless steel and clamped it down with more bulldog clips. I can swap it with a sheet of glass if I need to do PLA. The steel seems to be strong enough to stay flat in the middle when clamped at the edge.

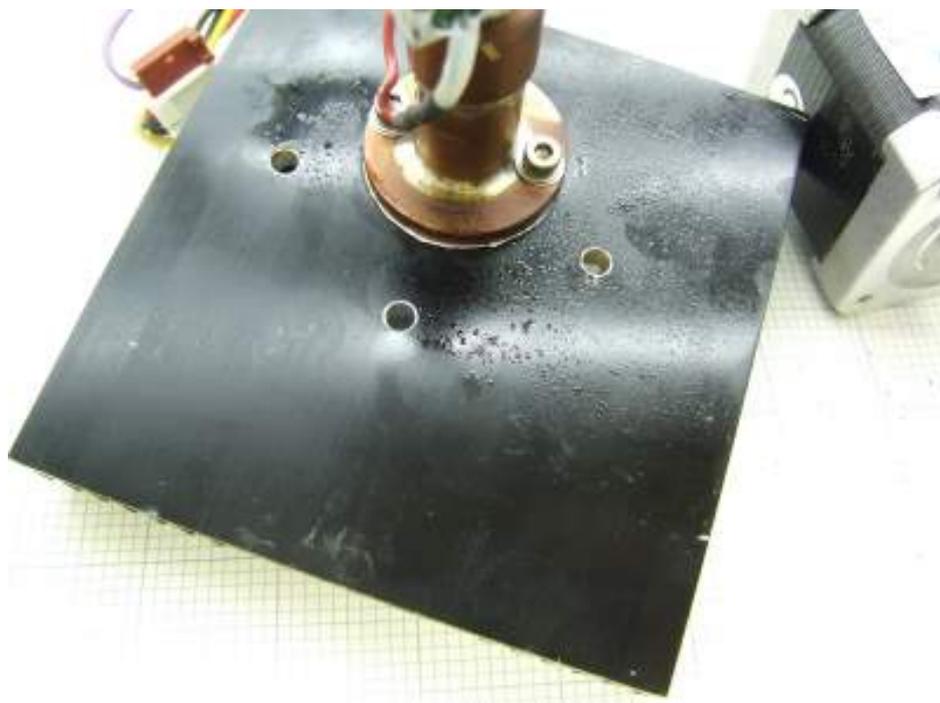


# Meltdown

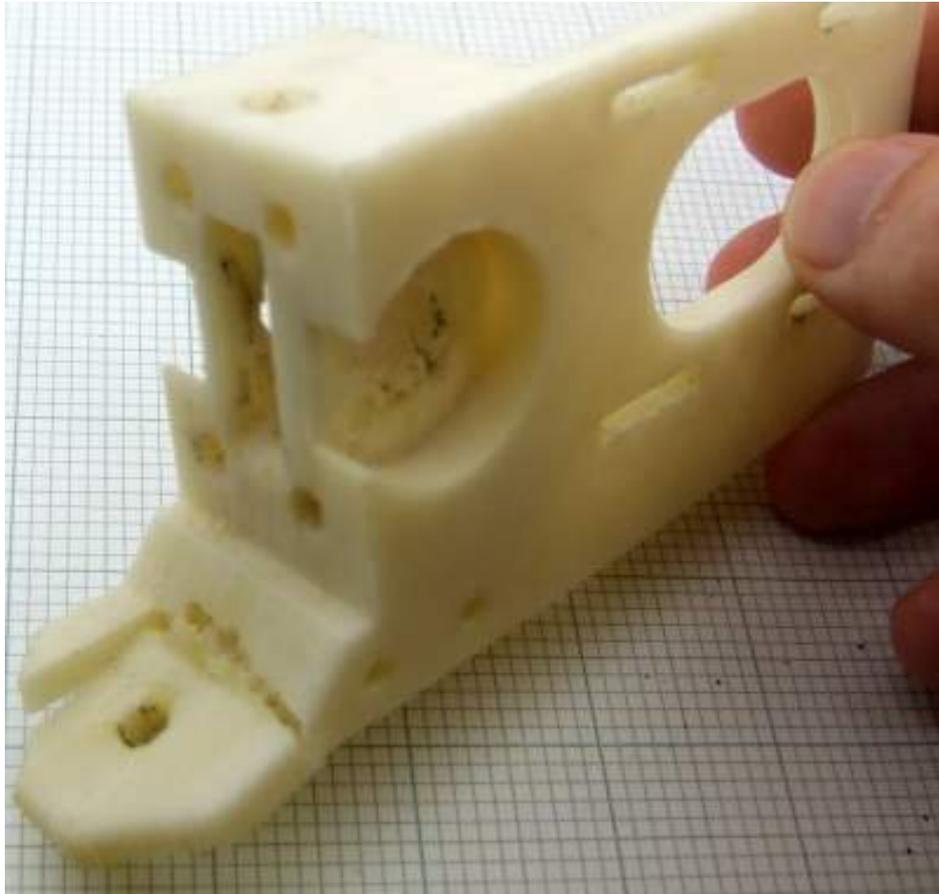
Thursday, 8th July 2010 by Nophead

While making its 18th child, my Mendel made a real pig's ear of laying down the first layer holes at the start of a build. So bad that the infill did not join to them and started curling upwards. I had to watch it a while before I realised what the problem was. The extruder had come loose and was bouncing up and down when the filament feed stopped and started.

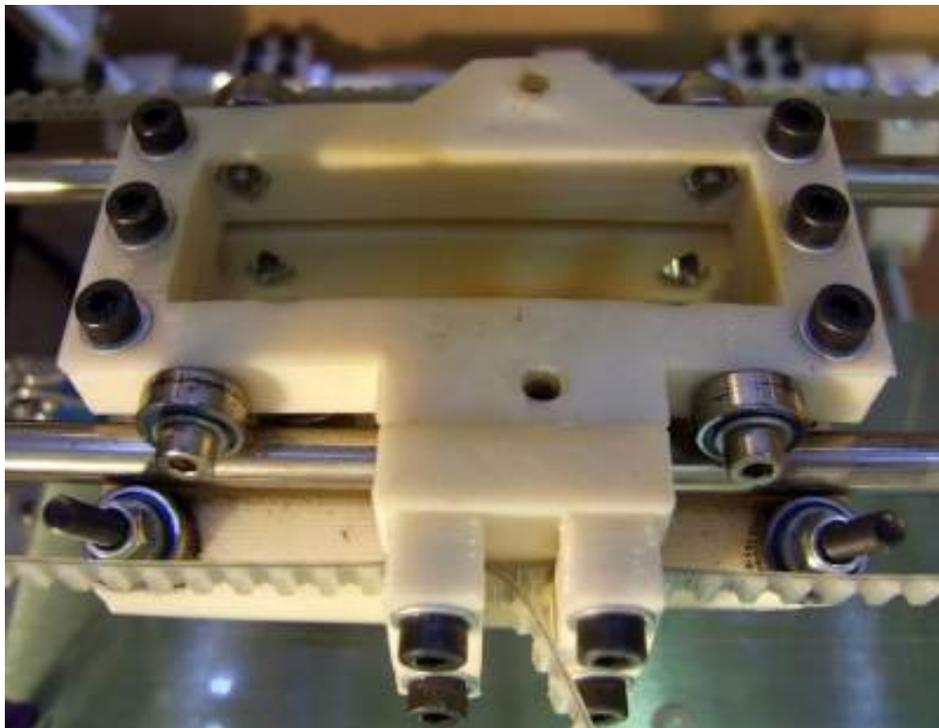
I thought it was just that the bolts had worked loose but after I tightened them it was still moving and there were some worrying crunching sounds, so it was time to strip it down.



The bottom of the heatsink is covered with a sticky deposit. It is some volatile component that boils off the ABS and condenses on cold surfaces,



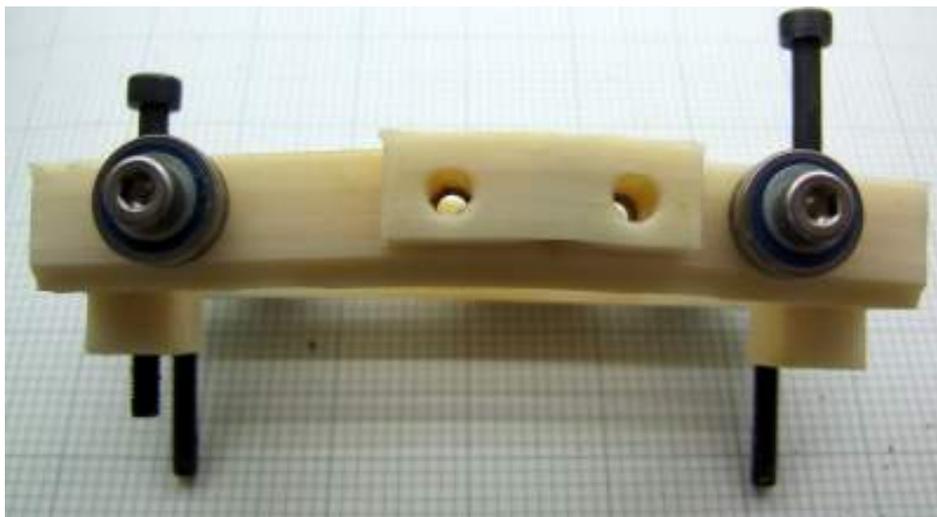
The main extruder bracket had broken and the carriage didn't look too good either: -



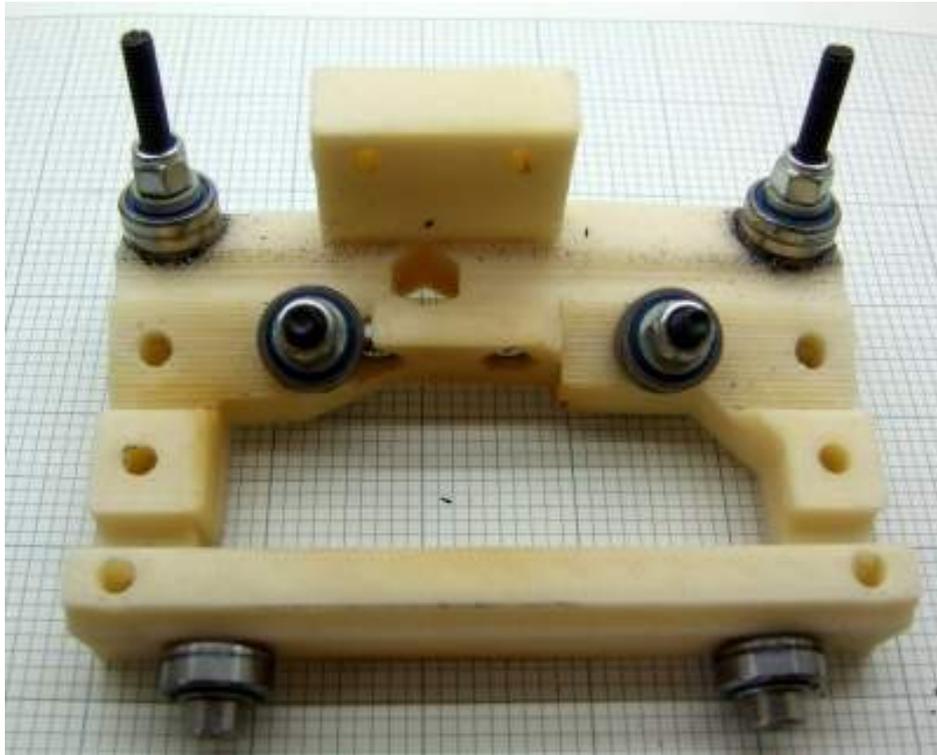
I stripped the carriage down as well and found that it was cracked and severely distorted.



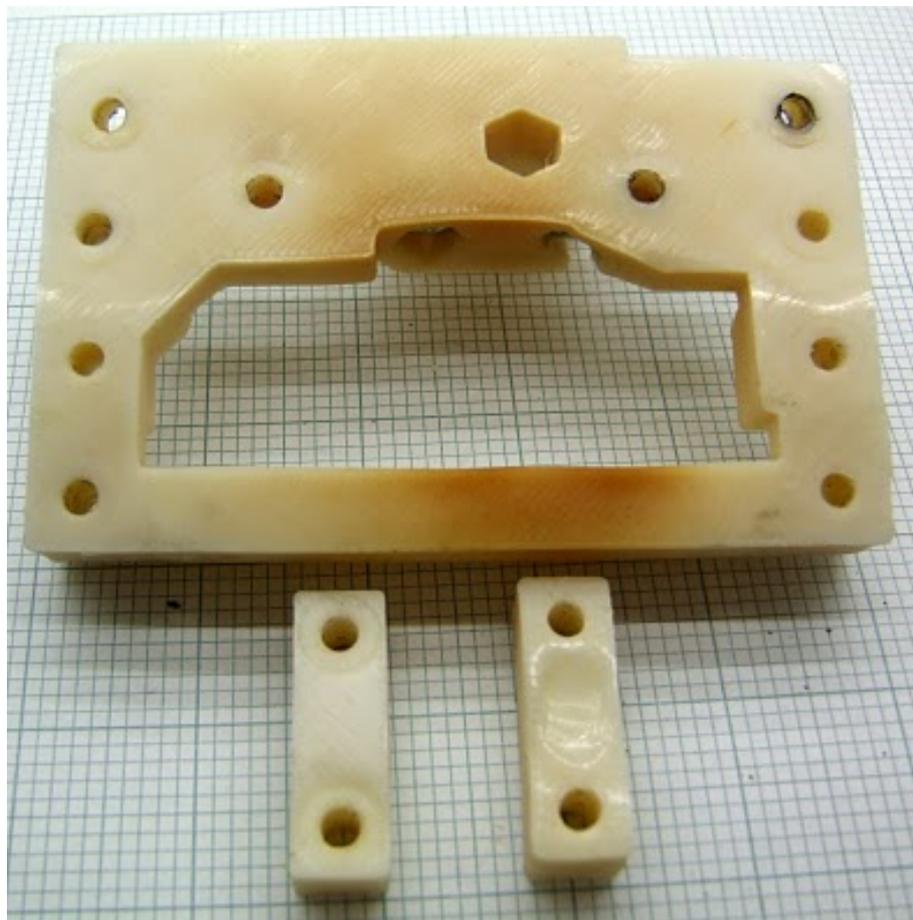
The main problem I realised is my modified hot end. Normally the insulator is locked into the chunky part of the bracket by a couple of M3 bolts through it. I can't get those in because my heatsink is in the way, so I rely on the mounting bolts and the upper carriage to take the extrusion force. On reflection, not a good idea!



The lower carriage is less deformed because the extrusion force does not pass through it.



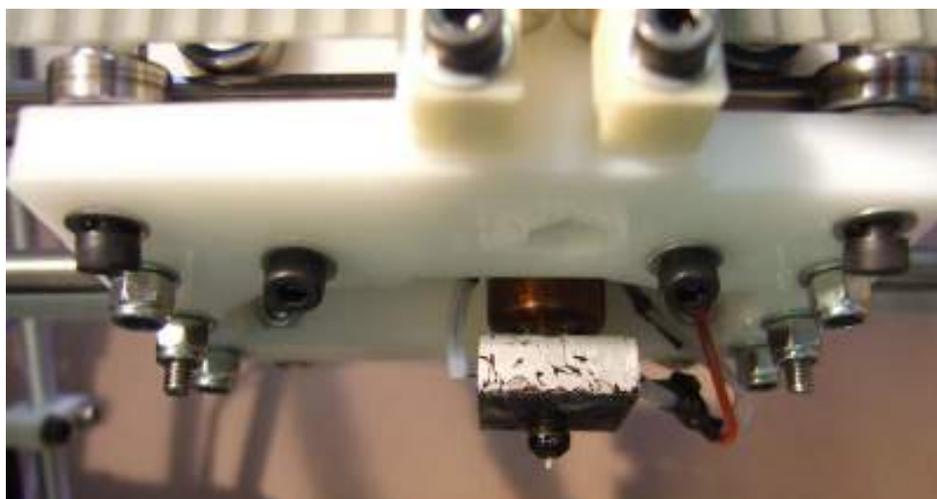
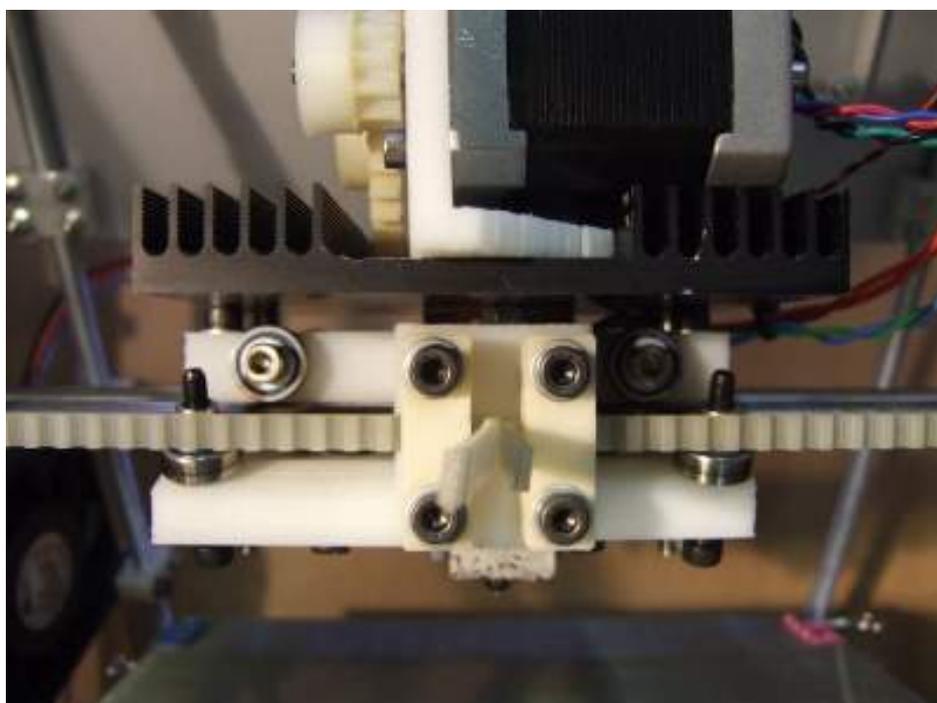
The heat rising from the bed and the extruder must be enough to soften the carriage and let it deform, but also it seems to have made the ABS weak and crumbly. Even the belt clamps have deformed.



This is after about 3 months of printing though so it isn't a big problem to replace them as long as you have spares. I had just printed a carriage before it failed so it was easy to replace but I had to print another extruder on HydraRaptor. You really need to have a full set of spares on hand, or have two machines.

I did various changes to make it more durable. The main thing is I fitted nuts under the heatsink so that no force goes through the carriage. I also put large penny washers on the top of the extruder bracket to reinforce the lugs. Ideally they should be a bit thicker but that would reduce the Z travel even further. The extruder motor clashes with the frame which reduces the height. Then my heatsink loses another 10mm or so and my heated bed loses 26mm. I am left with about 35mm which is only just enough to build the tallest Mendel part (the lower carriage).

I also used nyloc nuts in the captive positions in the carriage. The wiki advises against this as it may crack the plastic but it doesn't seem to be case with my ABS parts. Ordinary nuts don't stay tight because the plastic creeps.



I intend to fit some sort of heat shield to stop the heat rising from the bed reaching the carriage. In the mean time I have started fitting the front on my cabinet after the first layer is finished, when the bed temperature drops from 140°C to 110 °C. That can be up to 90 minutes into the build, so not convenient.

# A bit of a drag

Monday, 19th July 2010 by Nophead

One problem I have had, on and off, with Mendel is a tendency for the infill not to meet the outline. This was particularly bad with PLA. I have combated this by having some infill overlap and also extruding the plastic slightly faster than it should be, so that the solid layers are well stuffed. I don't have to do either of these things with HydraRaptor. I couldn't figure out what the difference was until I changed a reel of plastic recently. The first print on the new reel came out like this: -



The gap is always at one side like this, it is as if the infill is not centred within the outline. The reason, I have come to realise, is that the belt has some play in it because it is not infinitely taught. When the extruder pulls filament off a reel it exerts a force on the carriage, which displaces it slightly from where it would come to rest without any external force. Because the carriage moves, the filament only gets pulled from the reel at the local extremes of movement, the rest of the time it is slack. This causes small offsets in the filament paths. In particular, when it is doing zigzag infill it is using filament relatively quickly, so at the end of the zigzag furthest from the centre of the bed it is likely to give a little tug of the reel each time, causing the zigzag to stop short of the outline.

The conclusion is that the filament feed for a belt-driven moving-head machine needs to be very low drag. The hanging basket technique that I used on HydraRaptor is no good because it has to pull plastic out from under its own weight. Making the feed point high above the machine reduces the lateral drag on the carriage, but you can easily get enough vertical drag to deflect the x-bars upwards, or even lift the z-axis slightly because the backlash in the thread is only taken up by the weight of the x-axis.

The reason it was bad with PLA was because I was pulling it from a hanging basket and being very stiff, even a small coil needs a lot of tug.

The system I now use is a vertically mounted spool big enough to take 5kg coils, which last me a couple of weeks.



The bearing is just a stainless steel axle running in PLA bushes, lubricated with some lithium grease. It is low friction, but not as frictionless as a ball bearing. It needs a little friction to stop any in-balance in the coil causing the spool to spin to its low point. Also the faces of the spool need to be quite big to stop a loose loop of filament coming over the side. It pulls tight and jams if that happens.

I can take the spool apart to insert a new coil of plastic.



In general though I have to wind it all off and on again to get it tight and balanced enough to wind off smoothly. Since 5kg is about 800m it takes a long time to wind it onto a garden hose reel and then back on again. Someday I will get round to making a machine to do it for me. In the meantime I will make a second identical spool so that I can just mount the coil on one spool and wind it onto a second one to use.

# Rejuvenated Bed

Monday, 9th August 2010 by Nophead

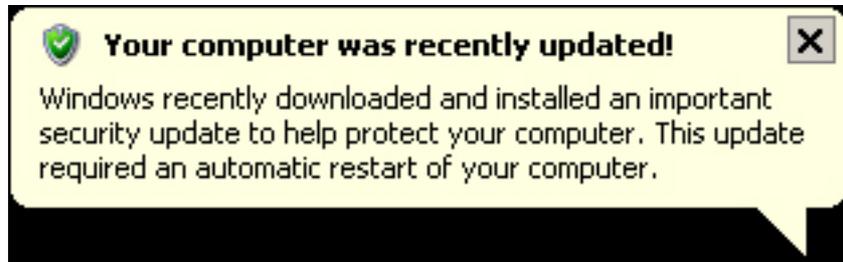
I put new PET tape on my heated bed at the beginning of July. Since then I have printed 15 Mendels on it, but on the last few I was getting problems with the parts not sticking. That is after about 700 hours of printing and ~15kg of plastic. I occasionally swab it down with Isopropanol to remove grease from finger prints, but Isopropanol is not a solvent for ABS. This evening I tried cleaning it with acetone instead. It dramatically increased the grip level, restoring it to new and making the parts hard to remove again! ABS must leave some traces behind on the surface of the bed and the acetone removes it.

So it looks like PET tape is almost fully reusable. It tends to get the odd blister where the corners of big objects overcome its adhesive and picks up a few scars from the odd accident with a knife. Apart from that it just needs cleaning with acetone about once a month.

# Friday the 13th

Monday, 23rd August 2010 by Nophead

When I got up last Friday morning my PC had this on the screen: -



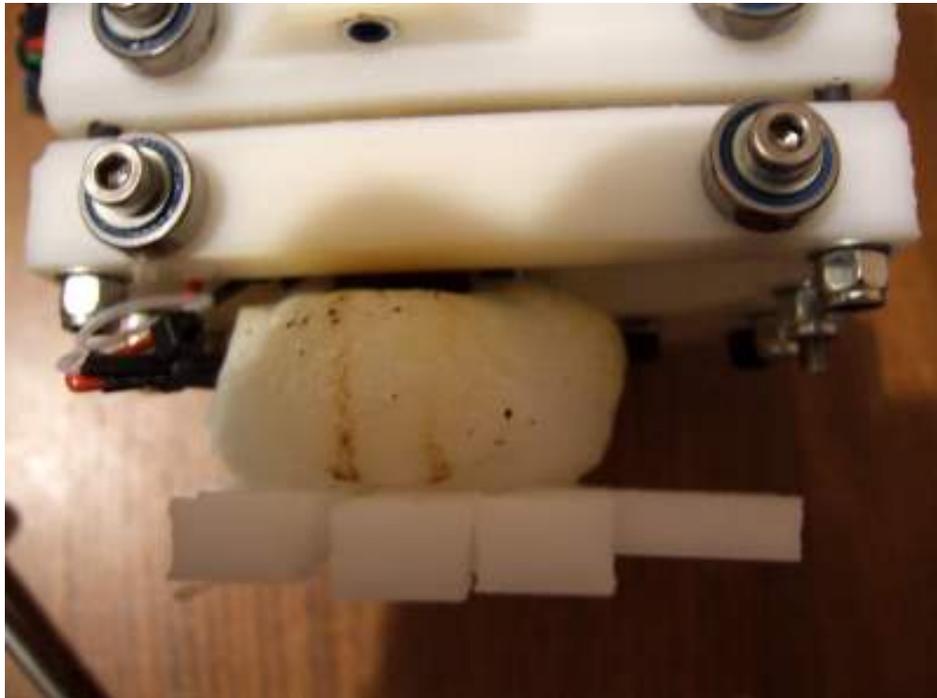
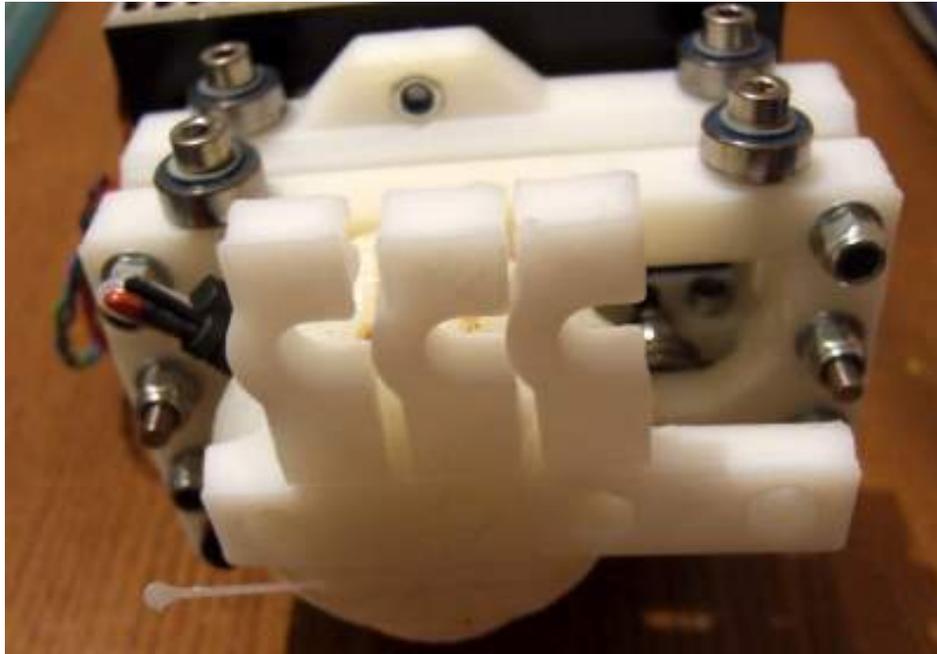
This is despite the fact that I had automatic updates set to ask me before installing. This was the result :-



The PC had stopped talking to my Mendel about half way through a seven hour build, so the axes had stopped moving but the extruder was left running for a few hours. The result was that the extruder was encased in a solid ball of ABS about the size of a tangerine. Thanks Microsoft! What I actually said at the time was less polite!

Of course I was planning to put some safeguards in the firmware and also run the machine from an SD card, but have never quite got round to it as I have been printing virtually non-stop for months.

I couldn't remove the extruder from the carriage because the blob was too big to go through the gap, so I had to dismantle the x-axis to release the carriage.



I have seen this happen to other people and it wrote off the extruder, but I thought this one should survive because it is mostly metal underneath the blob.

I tried using a loop of hot nichrome to slice bits of it off. The nichrome cut through OK, but the ABS closed up behind it, so it achieved nothing.

Next I tried a small circular saw attached to a Dremel. That worked OK, but threw off sawdust and bits of ABS hot enough to burn, even through light clothing. I got the bulk of it off that way but when I nicked one of the heater wires I decided to stop.

I got some more off by heating it with a hot air gun and pulling lumps off with a pair of pliers. That was OK but the whole extruder got too hot to hold and it was starting to soften the carriage.

I got the remainder off by running the heater up to 200°C and using a knife, wire cutters and pliers. It took me about 3 evenings in total to remove the blob and the machine was out of action for a week while I reassembled it and calibrated it again.

It now takes a bit longer to warm up, and extrudes more filament during the warm up process than it used to. I suspect therefore that the thermistor is reading low and so it is running hotter. It doesn't seem to cause a problem with the ABS that I am using. I had to increase the time I run the extruder to prime it after warm up though.

I also seem to have managed to bend one of my z lead-screws while sliding the x-axis bars in and out. It doesn't matter as the axis is constrained by the z-bars, but annoying as it rattles a bit.

All in all a bit of a disaster. It's running again now though, but I still haven't put a safeguard in my firmware. I will have to develop it on HydraRaptor and load it into Mendel between builds. I have disabled automatic updates!

# Freezing your bits off

Tuesday, 24th August 2010 by Nophead

Since I started cleaning my PET tape with acetone it can be hard to remove the parts from it sometimes. Somebody suggested trying freezer spray a while back, so I gave it a go.

I got this Arctic Spray, which is intended for freezing water pipes so that you can work on them without draining the water. I must admit I wouldn't fancy having a strict time limit if I was plumbing, you would have to be sure you had all the right tools and materials to start with. My occasional forays into plumbing rarely go to plan and usually involve a trip to B & Q in the middle.



I tried it first on an ABS part before the bed had cooled for any length of time, so it would be at about 100°C and the parts still soft. The part curled up at the edges and so came off easily. I thought I had ruined it by making it warp, but to my surprise it became flat again when it cooled. Still that seems a bit risky, and the spray isn't cheap, so now I cool the bed to 50°C with a fan and then spray any stubborn parts that I can't pull off. It works a treat but I don't know how long a can will last. It would have to be a lot of uses to make it worth the cost: £4.49 plus £2.20 on eBay. Hitting them with a block of wood and a hammer is a lot cheaper!

# Some corners like it hot

Sunday, 12th September 2010 by Nophead

Large objects with sharp corners, such as the Mendel z-leadscrew-base, produce enough stress to form a blister in the PET tape on my heated bed. These can only be flattened again by pricking the tape. I can't understand how air gets in and cannot get out again, but that is what seems to happen.

The blisters leave a small indentation in the object's base. It is only an aesthetic problem because the base remains flat, i.e. it doesn't rock on a flat surface.

Sometimes the blister allows the corner to peel from the bed towards the end of a build, allowing the corner to curl upwards a little. Generally I can avoid that by cleaning the bed with acetone before problem builds. I also use hexagonal infill on those parts and only two solid layers rather than three in an attempt to reduce the stress. When I design my own parts I round the corners, where possible, to prevent such problems.

A solution may be to use a sheet of PET rather than PET tape, but then you need to find a way of holding it down. One thing I have noticed though is that when I build a bed with four of the z-brackets closely packed the corners on the inside don't blister or lift. That must be because the air around them is hotter. As an experiment I added some little plastic walls to the build to act as baffles to keep the heat in as the bed moves through cooler air.

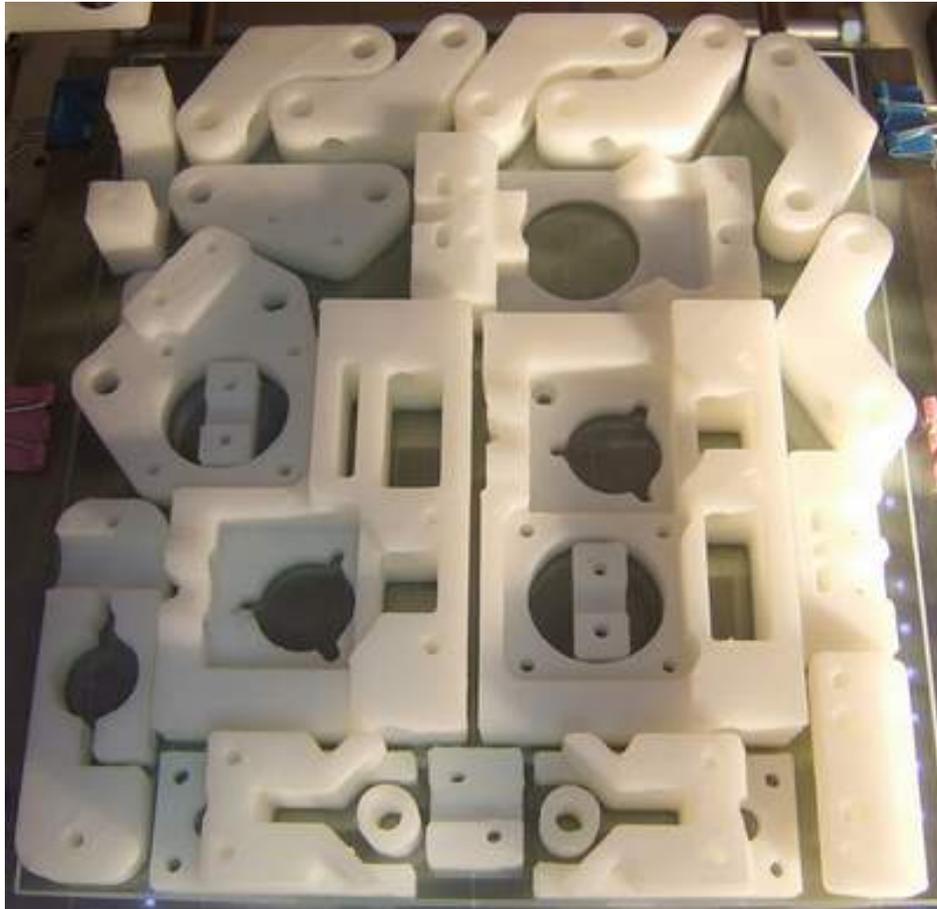


These have a 5mm thick base to help keep the tape flat and are 1mm away from the edge of the object. They work well and stop the blisters forming at the corners. They are very similar to Forrest's apron technique but their primary function is thermal rather than mechanical. A more general technique would be to build a thin wall all the way around the perimeter of the objects to cocoon them. I expect that would only need to be one filament thick and perhaps might give a similar effect to having a heated build chamber.

# Rebore

Tuesday, 28th September 2010 by Nophead

My Mendel has been very reliable and consistent running virtually 24/7, but about a week ago, after putting on a new reel of plastic things started to go wrong. The initial symptoms were that small parts built fine, in fact I printed a mini Mendel or Huxley that came out well: -





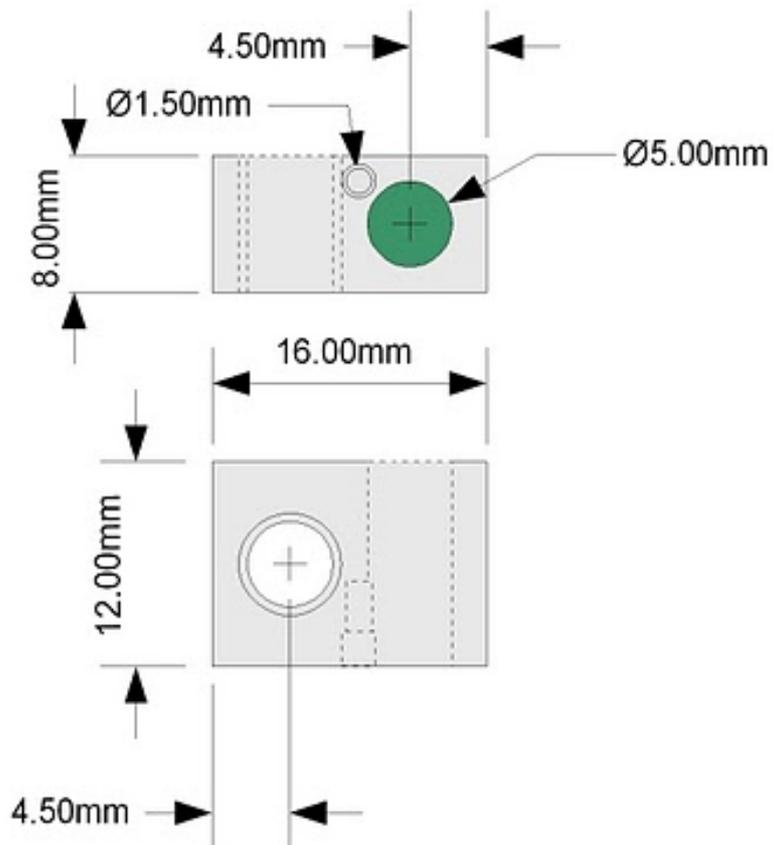
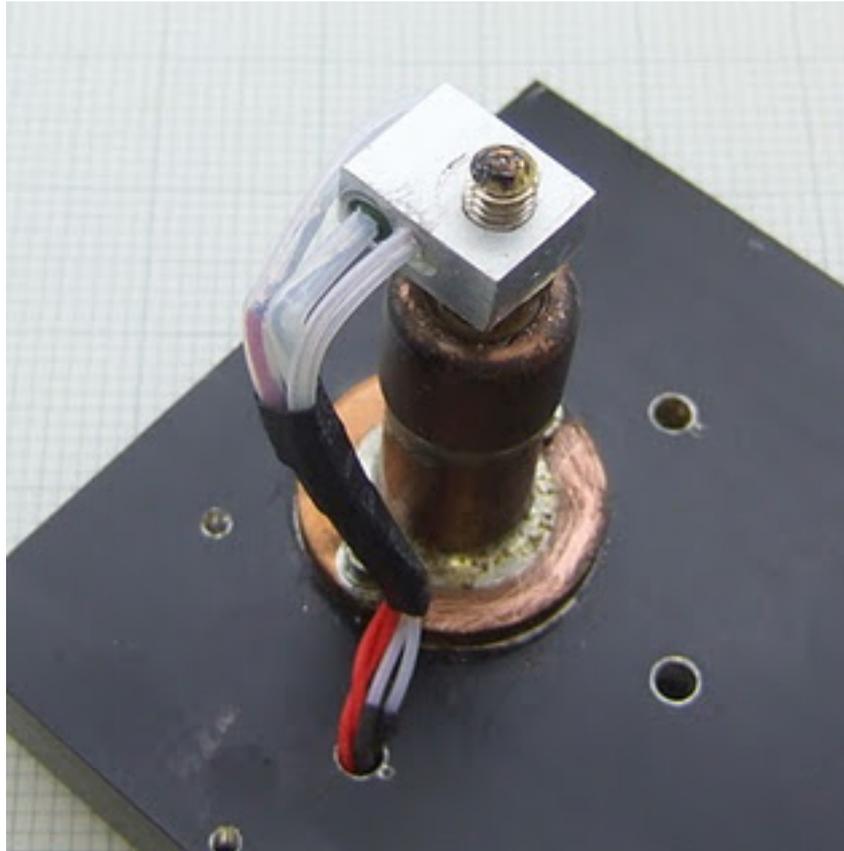
It took just two full Mendel beds, plus a few parts on HydraRaptor. I did the gears on Hydra for accuracy and the Bowden clamps at 100% fill because they look weak to me for the job they are intended to do. The plastic weighs 335g (including a Wade's extruder), slightly more than 1/3 of a Mendel by weight but the printtime is about 1/2, because small parts need finer filament. I printed most of these at 0.5mm whereas I do a lot of Mendel at 0.6mm.

But getting back to the problem, the quality of large parts had started to fall off a bit. They were coming out with blobs on the outside formed by the nozzle oozing as it moves from one object to another. These were not well bonded, so they could be simply scraped off with a fingernail, but something I had tuned out ages ago. Another change was that it was not doing 45 degree overhangs well, so it left filament hanging down in the tops of tear shaped holes. Again, not a big problem as they just get drilled out anyway.

I started to suspect the temperature was too high so I pushed the thermistor well into the heater block. Then the filament started jamming after the first layer (which I do very slowly). After a few attempts the extruder drive gear broke where the captive nut for the grub screw is. This seemed more like the temperature was too low, so I suspected the thermistor was no longer reliable. I decided to rebuild the heater assembly as my last one was put together in a hurry from parts left over from an experiment. It had been in the wars as well, being entombed in ABS and hacked out again, not to mention running almost continuously for about 2500 hours. Originally the thermistor was glued in with RTV silicone, but that was long gone and it relied on the wires holding it in place.

Since my original heater hack using a vitreous enamel resistor I had moved on to a smaller resistor on Hydra and found that worked better. The surface area of the block is a lot less and that is where most of the heat is lost from, so the amount of power required goes down. It also warms up faster of course, both due to less heat being lost and also less thermal mass. The resistor I

have settled on is a Vishay / Sfernice RWM04106R80JR15E1



The thermistor is drilled as close as I dare to the thread for the nozzle and then counter-bored so that the entrance is wide enough for the PTFE sleeving. The wires have PTFE insulation to withstand the temperature and the resistor is soldered with 300°C HMP solder. I think I could also get away with ordinary unleaded solder as well because of the length of the resistor leads, but I didn't want to chance it.

After a tip from [Giles](#) I used [Rothenberger high temperature glass rope adhesive](#) to glue the resistor and the thermistor. It sets in only half an hour, which is a big advantage over other things I have tried. I also used it to stick ceramic tape on the outside of the block to insulate it.

When I first heated it up the adhesive bubbled causing a downward slope in the temperature graph. I thought at first the thermistor had been dislodged by the blistering, but I think it was just temporarily cooled by the out-gassing. I should have heated it much more slowly the first time I think.

The new heater works much better than the old one. The warm up time to 255°C is about 280 seconds, whereas the old one took about 400 seconds (the bed takes about 350 seconds to get to 140°C). It also runs at about 70% to maintain 240°C while extruding, whereas the old one needed about 90%. The bang-bang control cycles much faster and only deviates by one degree. That is because of the close proximity of the thermistor to the heater. Because it is mounted between the heater and the barrel I can be sure the swing at the barrel is even less. I calibrate against a thermocouple inside the barrel, so any temperature difference across the block is calibrated out. It should be negligible though because the thermistor is also very close to the barrel and aluminium is a very good conductor. The extra power needed to heat the ABS when extruding 0.6mm filament at 32mm/s is about 10%, i.e. ~2W.

The new improved heater didn't solve any of my problems though. While reassembling the extruder I tried pushing filament through by hand. It was much harder than I remembered it was when I first built the extruder. At this point I was beginning to suspect the plastic was different in some way although it looked identical and was part of the same purchase.

I noted that the filament was coming out very curly. That was something I had noticed happening on both my machines when I do a test extrusion, but I had ignored it. I measured the diameter though and found whereas it normally swells to 0.7mm this was coming out oval and about 0.5mm by 0.6mm. It all fell into place then. I have read that the difference between straight hair and curly hair is whether it is round or oval. The only way the filament could be oval is if the nozzle aperture is no longer round. I put a 0.5mm drill bit through it and it started to extrude round, straight, 0.7mm filament again. The hole must have been partially occluded by the burnt plastic that tends to glaze the end of the nozzle. That caused the plastic to come out thinner and faster. It was fine when making objects with 0.5mm filament because it was still being stretched but when building with 0.6mm filament it was being compressed, so would hang loose if given the chance. The smaller

hole increased the barrel pressure, which is why it oozed. The plastic would be compressed more, so require more backing up to release the pressure and stop the flow. Also the extra pressure was too much for the pinch wheel when extruding at the top flow rate I use, which is 0.6mm at 32mm/s. I think the M8 hobbed bolt is below the ideal diameter for softer plastic like ABS.

I also re-bored HydraRaptor (with a 0.4mm drill) and that stopped the filament being curly as well. It seems nozzles need occasionally re-boring. I had assumed that the hot flow of high pressure plastic would have kept the hole clean, but not so.

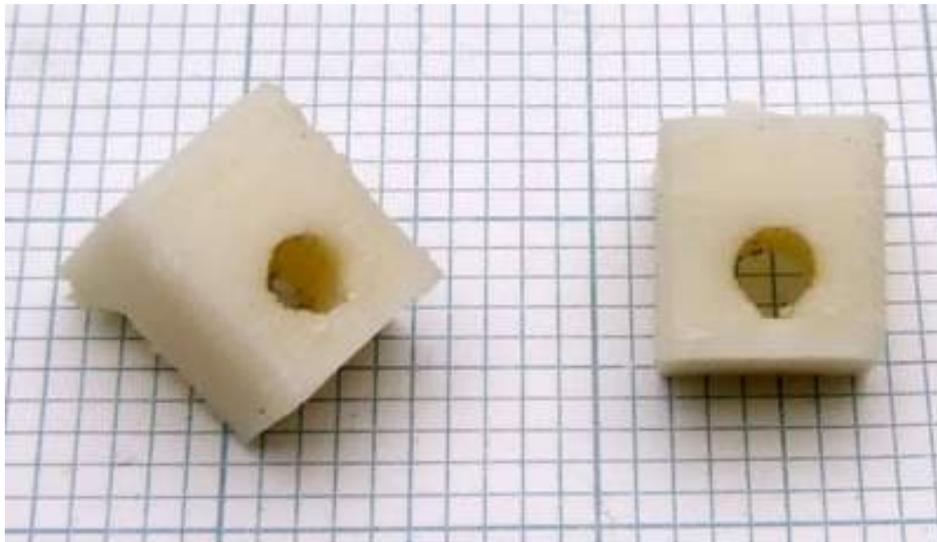
So a simple fault had my machine out of action for days because I didn't recognise what the symptoms meant collectively.

# Monthly maintenance

Saturday, 13th November 2010 by Nophead

So, after just over a month more of continuous use of my Mendel, I noticed the filament not spanning gaps well. It had also gone curly again. I measured it at about 0.6mm extruded into fresh air, so decided it was time to bore out the nozzle again. I do this with a 0.5mm bit held between my fingers with the nozzle hot. This restored the diameter to over 0.7mm again, so it is able to extrude 0.6mm filament with enough stretch to span gaps. Looks like this needs to be once a month maintenance.

Another failure I had was two of the bed support lugs sheared off the 360 y-bearings: -

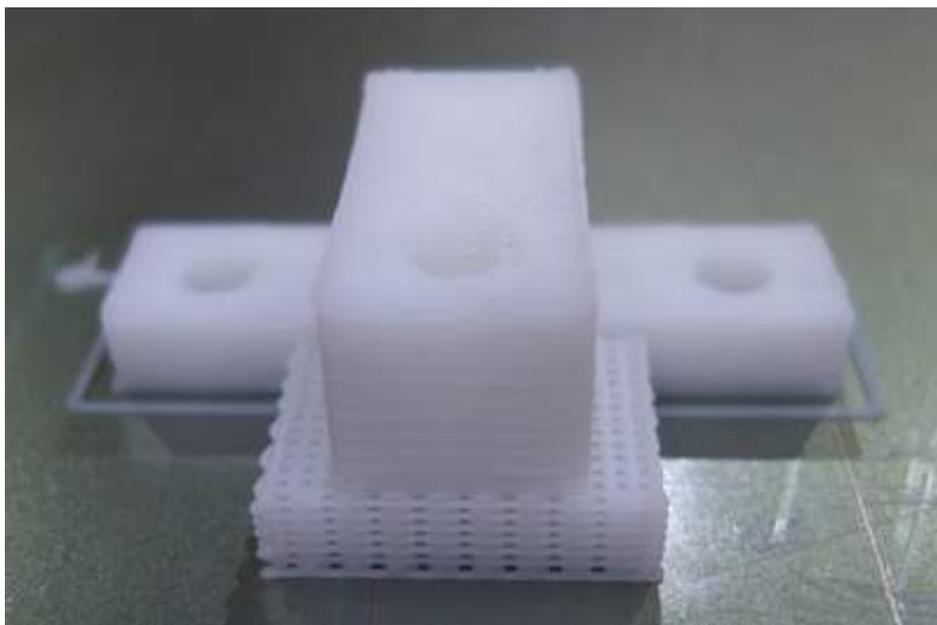


-  
These are under more load on my machine because I have a heavy metal bed. They also get some strain when parts are being removed from it. Rather than strip the machine down and replace the y-bearings, I made a new part that sits between the two y-bearings and supports the bed on three rather than four points.



If the bed is slightly flexible, for example when made from Dibond, then all four corners can be levelled independently. When it is stiffer, for example 6mm aluminium, then you can only adjust three points independently. In fact, one of those can be fixed and then there are only two points that need adjusting.

I made this using the support material option of Skienforge for the first time. To use it I have to enable the raft module but then disable the raft by setting the base layers and interface layers to zero. Without the cross hatch option the support material is easier to remove, but it tends to come away from the bed. For raft-less support the first layer of the support could do with being solid.



Other persistent problems I have are connectors losing contact, so reseating them once a month

is good idea. The constant vibration and heat cycling seems to make connectors unreliable. Screw terminals with ferrules over the wire end seems to be the way to go.

The M8 nuts on the frame shake loose, I wish I had used lock washers! Also the grub screw in the pulleys eventually work loose after months and the one in the extruder drive gear needs tightening after a few weeks. It seems to be impossible to keep anything tight in plastic, especially when it is oscillating backwards and forwards. The plastic gives a little and that movement causes screws to work loose. Perhaps some thread-lock in the set screws would do the trick, but I am not certain that the screw might need to be tightened to take up slack caused by the plastic creeping.

Of course running a machine 24/7 is not what most users will do, so it will take many months of normal use before these types of fault manifest.

# Cr&egrave;me br&ucirc;l&eacute;e

Thursday, 16th December 2010 by Nophead

This is what happened when the thermocouple fell off my heated bed: -



It happened while both myself and my wife were at work so the machine finished the build. When I came home the room stank of fumes.

The bed temperature will have been limited to about 170°C by the thermal cut out I have in series with the heater for safety. Since it was making a bed of six and it went wrong about 1/3 of the way through the build, they will have been cooking for about 4 hours.



Unsurprisingly the bottom of the object shrank and went brown. What was surprising was that the bottom layer became transparent and glass like. So glass like that I cut my finger on it. The meniscus edge was razor sharp. It seems to have softened over time though, this happened a few weeks ago.

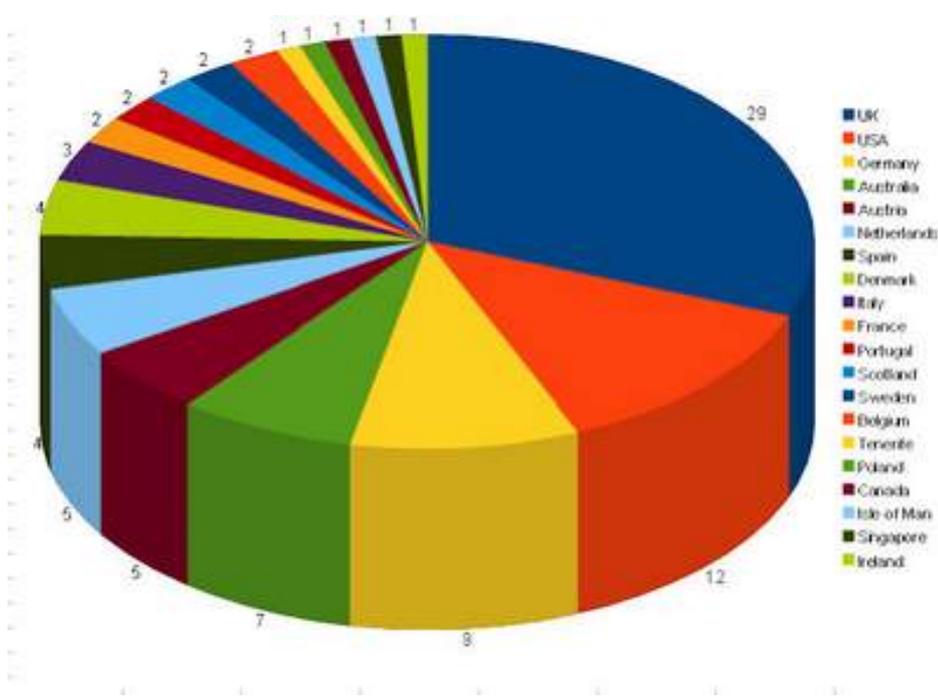
Perhaps it might be a useful process if you want a transparent window on the base of an object. You could lay down a single layer and then cook it for a few hours at 170°C and then deposit the rest of the object on top of it.

# 101 Mendels

Saturday, 18th December 2010 by Nophead

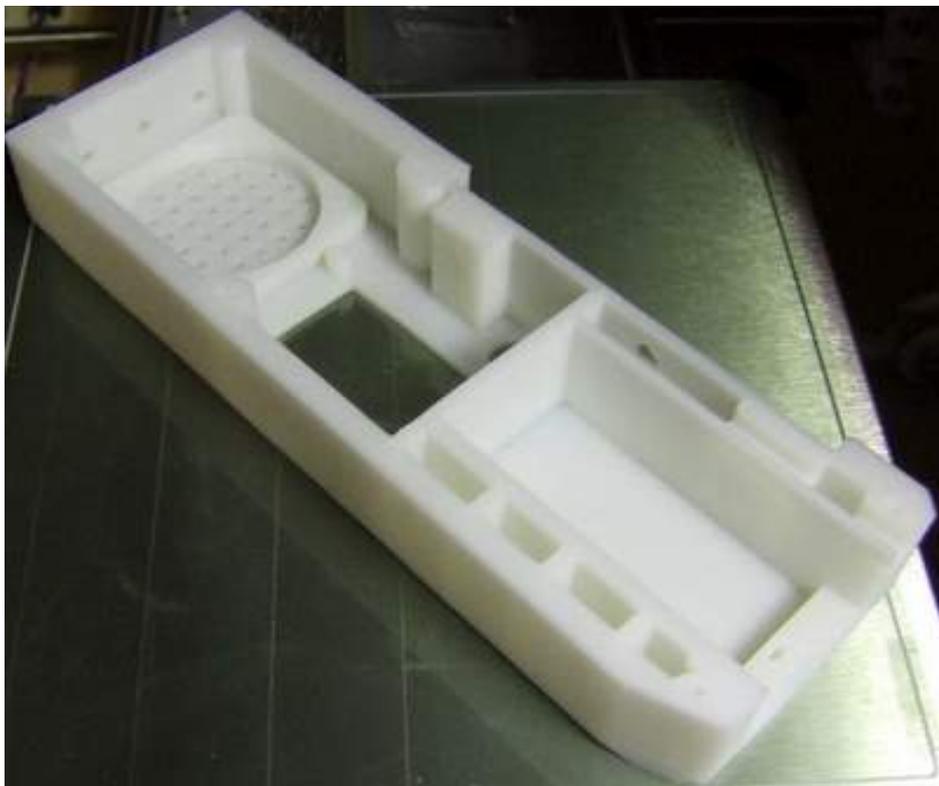
From March up until a week ago I have run my Mendel as close to 24/7 as I can and it has printed 101 Mendels, with a bit of help from HydraRaptor. During all that time I have been able to sell them as fast as I could print them but there has been a dip in demand running up to Christmas, so I stopped printing on Monday, having built up a small stock.

I have shipped parts to England, Scotland, Isle of Man, Ireland, Sweden, Denmark, Belgium, Netherlands, Germany, Austria, Poland, France, Spain, Portugal, Italy, Tenerife, USA, Canada, Australia and Singapore.



It seems weird now to have a quiet house and not have to stay up until midnight every night to start the overnight build. It does mean that I have time to blog again though, and print things that are not Mendel parts.

I have been printing parts of a Milestag laser tag gun for a friend of mine. I recommended CoCreate to him and he has taken it and run with it. His first design is way more sophisticated than anything I have managed so far. It is a large device broken up into parts that just fit on my 200mm bed. Here is one of them: -



You can see the rest in Tony's blog <http://funwithelectrons.blogspot.com/2010/12/milestag.html>.

I think a machine printing 101 copies of itself must be a bit of a milestone in the RepRap project. That is about 100kg of plastic and not far off 4800 hours of printing in about 6000 available. It is testimony to the reliability of the mechanical design and if anything, the quality of the parts is getting better as I tweak the settings.

# Crackers

Sunday, 26th December 2010 by Nophead

My wife has assembled her own Christmas crackers from kits in recent years. She puts in much better gifts than even the more expensive commercial ones contain. It did backfire one year when she put a handkerchief in one and it ended up with a powder burn from the explosive!

This year she asked me to make some reprapped boxes instead to contain the usual cracker contents and look decorative on the table. The explosive element to be provided by a party popper. This is what I came up with: -



Having zero artistic ability myself: the star is Christmas star by andrewar from Thingiverse and the tree was grafted from the frame vertex of the Holiday Prusa Mendel by kliment.



My contribution to the design is the box. The base dimensions were determined by the hats my wife wanted to use and the height by the party popper diameter. This one also contains a magnetic bookmark, two chocolates, two PLA snowflakes and a charade instead of the usual bad joke or motto.



The lids had to be printed hollow side down because of the raised design on top. The gap is too big to be spanned without a lot of droop, so I used the support facility in Skienforge. I set the "support gap over extrusion perimeter ratio" to 10 to make it easier to remove and waste a little less plastic. I have no idea why the ends of the support are all in slightly different places.



It was still quite tedious to remove, so I tried Adrian Bowyer's technique of using oil to reduce the bonding. I knew the roof of the lid started at 8mm, and my host software prints the height of the current layer, so I just waited until it had finished the support and painted it with machine oil using small paint brush, while dodging the head. It worked very well and made the support easy to remove.

Here you can see the scars left behind, probably where I missed with the oil: -



I removed the scars by waving a hot air gun over the plastic.



The unsupported area sags a little and that makes a visible pattern on the top as there are only three solid layers. I think that actually makes it look more decorative by adding a textured border: -



The removed supports could be glued together and used as streamers.



These cracker replacements went down very well with both our families. They make a lot less mess on the dinner table and could also be reusable, but they all asked to keep the boxes, which was of course our original intention.

The files are available [here](#).

Merry Christmas!

# Round robin

Tuesday, 28th December 2010 by Nophead

I have been making a few small tweaks to my host software to improve quality recently. One such tweak is the order in which islands of an object (or objects) are visited. By "island" I mean a closed outline and the holes and infill that it encloses. Skeinforge seems to always go for the nearest island, so when it finishes a layer it starts the next layer on the island it has just done and revisits the others in the reverse order.

This means that the plastic is added to the hottest island first and the coldest last. When an island is small it can mean that the layer below is still molten when the next layer is added. I simply reverse the order of every second layer so that the islands are visited in a round robin order. That means they all get the same time to cool down before the next layer is added.

The only downside is one extra long head move each layer from the last to the first island. If your machine leaves strings that is not ideal but mine hasn't since I started reversing the extruder. That also makes the Comb and Tower modules of Skeinforge redundant.

## Tip top top layer tip

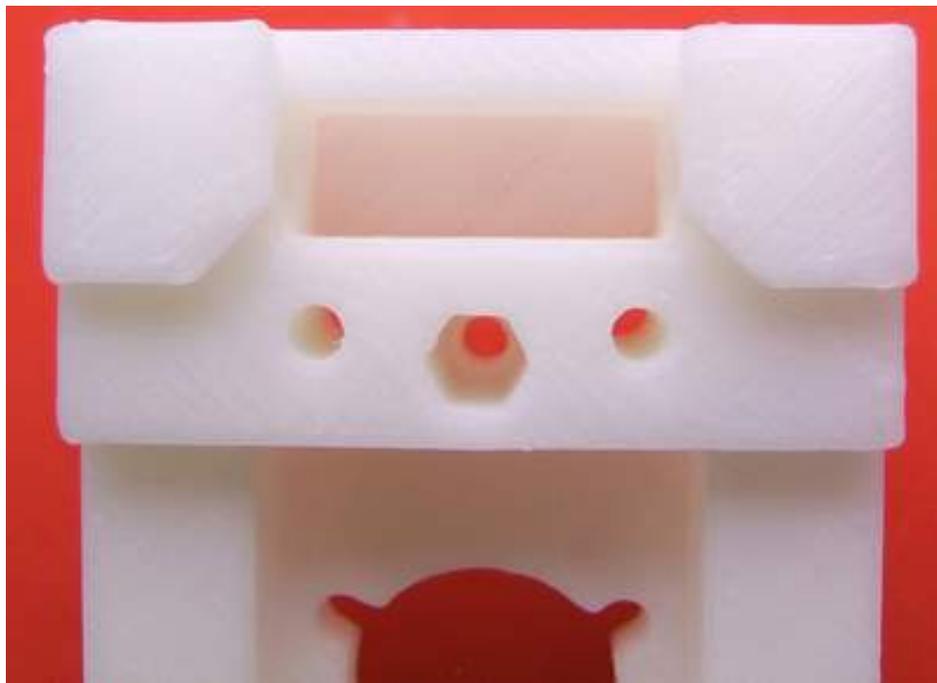
Wednesday, 29th December 2010 by Nophead

When I first started printing on my Mendel I found it difficult to get the top layer infill solid and meeting the edges. It behaved differently to HydraRaptor, but since it was a different bot and extruder and I had also changed to a different type of ABS and updated Skeinforge it was hard to work out what the problem was.

The first problem I identified was backlash caused by the filament dragging on the carriage. I fixed that by switching from basket feed to spool feed, see [hydraraptor.blogspot.com/2010/07/bit-of-drag.html](http://hydraraptor.blogspot.com/2010/07/bit-of-drag.html). That made a big improvement but I also set the "Infill Perimeter Overlap" ratio to its default value of 0.15, where previously I had used 0, and also increased the amount of plastic above the theoretical 100% value.

That is the way it stayed until very recently when I made a discovery about Skeinforge. A new parameter had appeared when I updated: "Infill Interior Density over Exterior Density" ratio, which defaults to 0.9. This seems like a good idea to make inner solid layers a bit less dense. It helps if the bottom layer is a bit too low by giving somewhere for the excess plastic to go. As I was using a little excess plastic anyway it seemed a good idea.

I had noticed that some outer surfaces are never well filled even when other surfaces on the same object are. Here is an example in the bottom of the well in this bracket.



I only realised recently that this was because the 0.9 is applied to some exposed surfaces, not just to internal ones. I set the value to 1.00 and things got a lot better. Not only does it fix the problem above, but it helps to make the other top surfaces solid. I normally use three solid layers to get a

good surface on top of sparse infill. But with the first two at only 90% the top layer is still lacking in plastic. That is why I had to use a higher flow rate than theory predicted. Once I got rid of this parameter I could reduce the flow rate and still get a solid top surface. In fact, I can get a reasonable top surface with only two solid layers now.

Another side effect of having the flow rate too high to compensate for the layers below being only 90% was that the top layer was being forced in. When the infill goes from two different directions and meets in the middle I was getting a ridge because the plastic would be being forced into a channel that was a bit too small for it.

Yet another issue I had noticed was that some side walls were inexplicably lumpy. I.e. not in positions where the filament starts or stops. Examining the slices I realised that it was caused by the infill displacing the outline. This was because I had a 15% overlap. Since I made the inner solid layers solid I found I don't need this any more and those bumps have gone away.

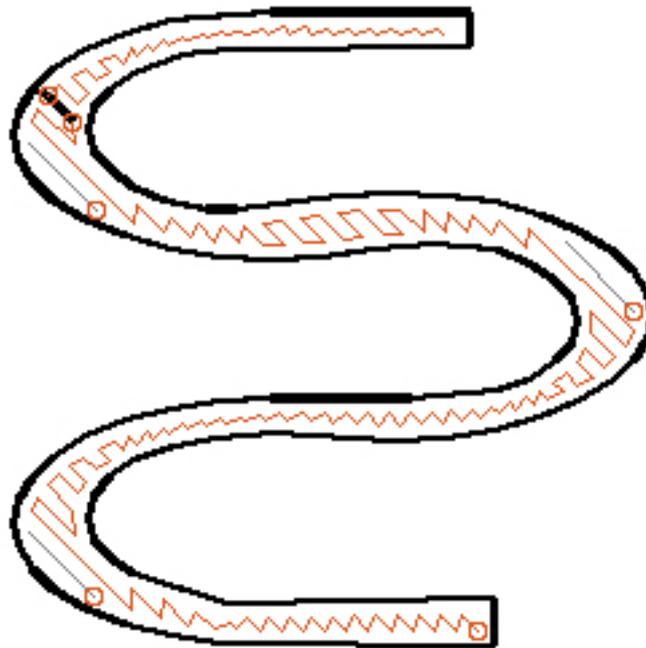
So in summary I was using excess flow rate and infill overlap to compensate for inner solid layers (and some outer ones) not being 100% solid. The side effects were lumpy walls and ridges on the top surface.

# Frequency limit

Friday, 31st December 2010 by Nophead

I currently do my infill on Mendel at 36mm/s. The machine can go faster but the extruder flow rate maxes out at about 40mm/s when extruding ABS at 0.6mm, so 36 is a good safety margin for reliability and quality.

Although the speed is limited there is no real limit on how fast it can change direction. Suppose you make something 2.4mm wide with 0.5mm filament. E.g. a Mendel spring: -



Each wall will be 0.6mm wide leaving a 1.2mm gap in the middle. That gets filled with a zigzag infill where the head moves to within 0.3mm of each wall, so the head moves about 0.6mm on each stroke. At 36mm/s that makes 30 complete oscillations every second. 30Hz is a pretty high frequency for a mechanical system!

What actually happens is my y-axis starts to resonate. Over a few cycles the amplitude of the oscillation builds up and the infill overshoots the outline leaving a serrated edge.



The torque of a stepper motor is zero at rest and increases as it is displaced, so in that respect it behaves like a spring. That springiness together with the inertia of the rotor gives a resonance at hundreds of Hertz, known as mid band resonance. When the load is rigidly coupled, as in this case, the mass of the load brings the resonant frequency down.

As I don't get any missed steps I think the springiness might actually be in the belt rather than the motor. Timing belts have metal cables in them so that they don't stretch, but that makes them stiff, so they don't like to bend round a tight radius. That means the belt has some springiness being pulled round the pulley. A bigger pulley would be better but that would reduce the effective stiffness of the motor, so might actually make things worse. A lighter bed would be good but I haven't found a way to ensure it is flat without going to 6mm tooling plate.

I fixed the problem in software by slowing down the infill that has a high frequency content. I examine each infill path, one axis at a time, and convert it into a list of lengths between changes in direction. I then find the shortest wavelength over three cycles (less than three cycles is not long enough for the resonance to build up). I do this for X and Y directions and save the shortest of the two wavelengths. When I extrude the path I work out the frequency from the pre-calculated wavelength and the desired speed. I then compare that with a limit for each machine and reduce the speed if the frequency limit would be exceeded. I could have a separate frequency limit for each axis but I don't like the idea that the orientation of an object affects how it builds, so I pick the worst axis when deciding the limit.

I set the frequency limit to 20 Hz on my Mendel and 16 Hz on HydraRaptor. HydraRaptor does not

show the overshoot problem, but it makes horrible growling noises and shakes the house. The machines make more interesting noises now because each infill run that hits the limit is extruded at an arbitrary lower speed. The overshoot is completely cured.



The builds are a bit slower and in some cases a long infill path will be slowed down by a short section that is high frequency, often a section between a hole and the outline. A more complicated solution would be to isolate the high frequency section and extrude the rest of the path at full speed.

# ABS on PETG

Monday, 10th January 2011 by Nophead

I have been using PET tape on my heated bed for a long time now. It works very well as long as I clean it with acetone about every 100 hours. It does need a high temperature (145°C) for the first layer with some types of ABS though .

It seems to last forever, the only failure mode is that large thick objects with sharp corners can defeat the adhesive and raise blisters at the corners near the edge of the bed. I solve that by building little heat shields to keep the corners warm. I am always on the lookout for something better though. It would be nice to get rid of the lines where the tape butts against itself.

A friend gave me a sheet of 1mm thick PETG to try. I clipped it onto my heated bed, and thinking it would behave like PET tape, I ran a build using the same temperatures.



Big mistake, PET has a glass transition at 75°C so it went soft and floppy. The object stuck to it very well and was hard to remove, but after getting a knife under one corner, it peeled cleanly. However it left an impression in the PETG.



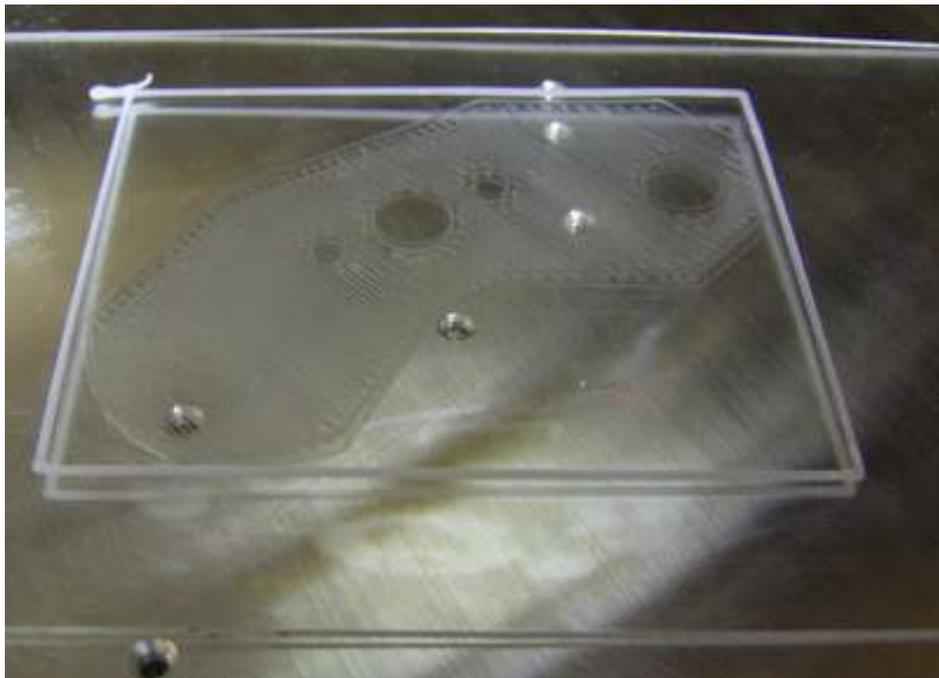
The base of the object is flat but the filaments are more ridged because they sank into the sheet rather than being squashed.



When the sheet cooled down it warped badly, so that was the end of that experiment. I did have a small offcut though so I tried again at 70°C.



This time the object warped badly. It stayed stuck to the PETG but it warped the sheet. The adhesion was less and the object was easily peel-able. The PETG warped where the object was but the rest of it stayed flat. The heat of the object must have been enough to tip it over its glass transition locally. It left an impression, but not as deep as the first time.



The filaments on the bottom were squashed tighter, not as smooth as when using tape.



So a failed experiment. It is a shame because at high temperatures it bonds very well but, unlike PC, it still peels, but it is no good if it doesn't remain rigid. Wikipedia does say that PETG has a lower melting point than PET. It doesn't mention how it affects Tg, but it gives the Tg of PET as 75°C. Odd then that PET tape doesn't go soft at 75°C. My next trial will be Mylar, which is another form of PET (BoPET).

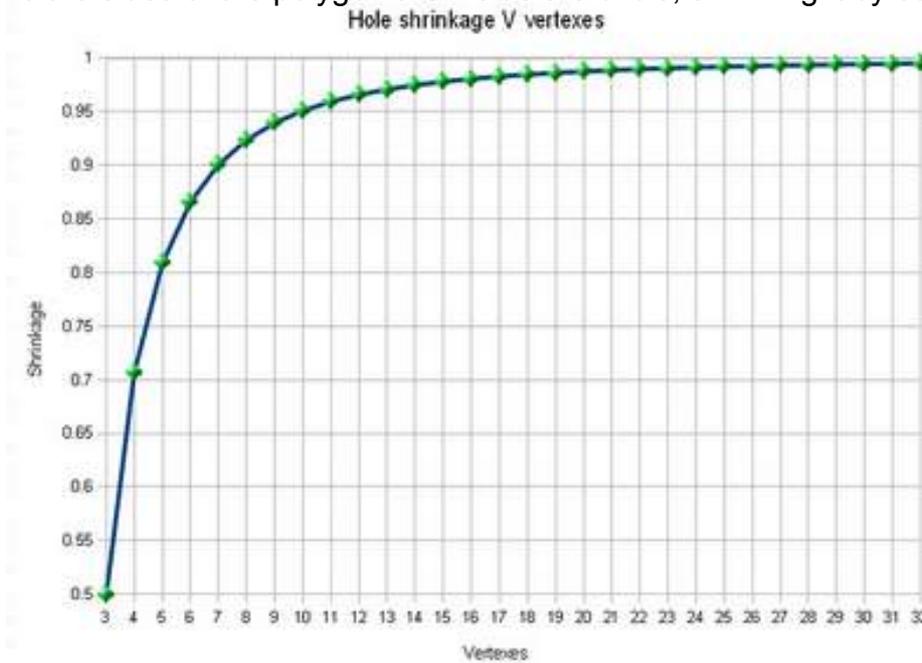
# Polyholes

Saturday, 5th February 2011 by Nophead

When Reprap machines print holes they tend to come out undersized, even if the linear dimensions of an object are spot on. There are several effects that all make holes smaller than they should be: -

## Faceting error

When CAD systems convert cylinders to triangles they produce a polygonal prism, so holes represented in an STL file are polygons with their vertices on the circumference of the original circle. That means the sides of the polygon are inside the circle, shrinking it by  $\cos(\pi / n)$ .



You need 10 vertices to reduce the error to 5% and 22 for 1%. So this error quickly becomes small as n increases but that creates another error:-

## Segment pausing

When a circle is broken into a lot of little segments the start up time for a segment becomes significant. Reprap in the past has suffered from this really badly and I am unsure what the current status is. Slow serial comms and complex floating point firmware add pauses where extra filament can ooze from the nozzle.

I have never suffered from pausing because I use a 100Mbit Ethernet connection, which has a very low latency, and the data is transmitted in binary and in the units my firmware works in. This means that no further processing is required other than calculating which of the three axes has to go the furthest. However, I use trapezoidal acceleration on each segment, so for very short segments the average speed will be a little lower.

## Arc shrinkage

When a flat strip of filament is bent into an arc there is too much plastic on the inside of the curve and too little on the outside. That makes both the inside and outside edges a smaller diameter than they should be. Adrian calculated a formula for it here:

<http://reprap.org/wiki/ArcCompensation>. The formula comes out with a figure that is too small though. I think there is a secondary effect:

## Corner cutting

When filament is dragged round a corner it likes to take a short-cut. This depends on how elastic the filament is and how much it is being stretched. I think when the nozzle moves in a circle the filament is continually trying to cut the corner and ends up forming a smaller diameter circle. I think this is the dominant effect on my machines.

Obviously, if you lie to Skeinforge about how wide your filament is that will make holes even smaller, but that is just a calibration problem.

Ideally all these effects should be compensated for in the slicing software but what has happened instead recently is that people are using parametric values in OpenScad to tweak the holes to come out right on their machines. That is the wrong approach because when the holes comes out smaller than they should be, without the slicing software compensating for it, then the infill doesn't meet it as tightly as it should do.

When I started printing Prusa Mendel parts I found the values in the configuration file far too big. I have also noticed this when downloading some designs from Thingiverse. That implies that my holes shrink less than a lot of other peoples, which is odd because all the effects above don't depend on the machine, apart from segment pausing.

Some of the holes in Josef's parts are octagonal. That made me realise that polygons with low vertex counts don't shrink. The inside of the hole is defined by straight lines and they get extruded in the correct place. What does happen though is that the corners of the polygon are rounded. As long as the polygon has a small number of vertices, the corners are far enough from the circle that they can be rounded without impinging on it. The ideal number of vertices is when the corner cutting just meets the circle.

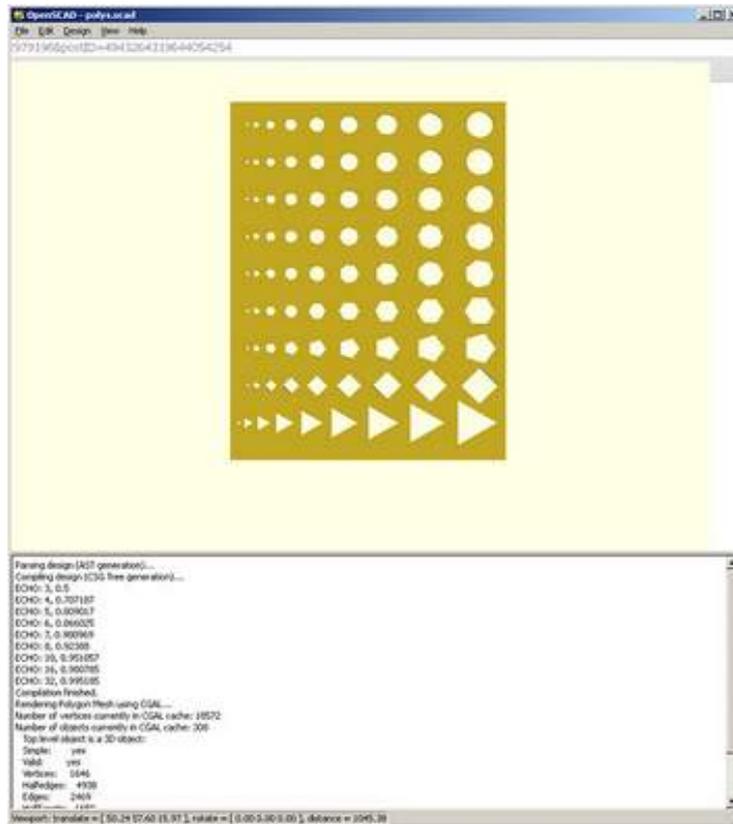
I decided to investigate this using OpenScad. I made a script that generates holes from 1 to 10mm with vertex counts from 3 to 8, 10, 16 and 32. The diameter of the holes is increased to make the polygon edges tangential to the circular hole. I.e. removing the faceting error by dividing by  $\cos(\pi / n)$ .

```
difference() {      cube(size = [95,125,3]);      for(i = [1:9]) {  
  assign(v=[3,4,5,6,7,8,10,16,32][i - 1]) {      assign(shrink = cos (180 / v)) {
```

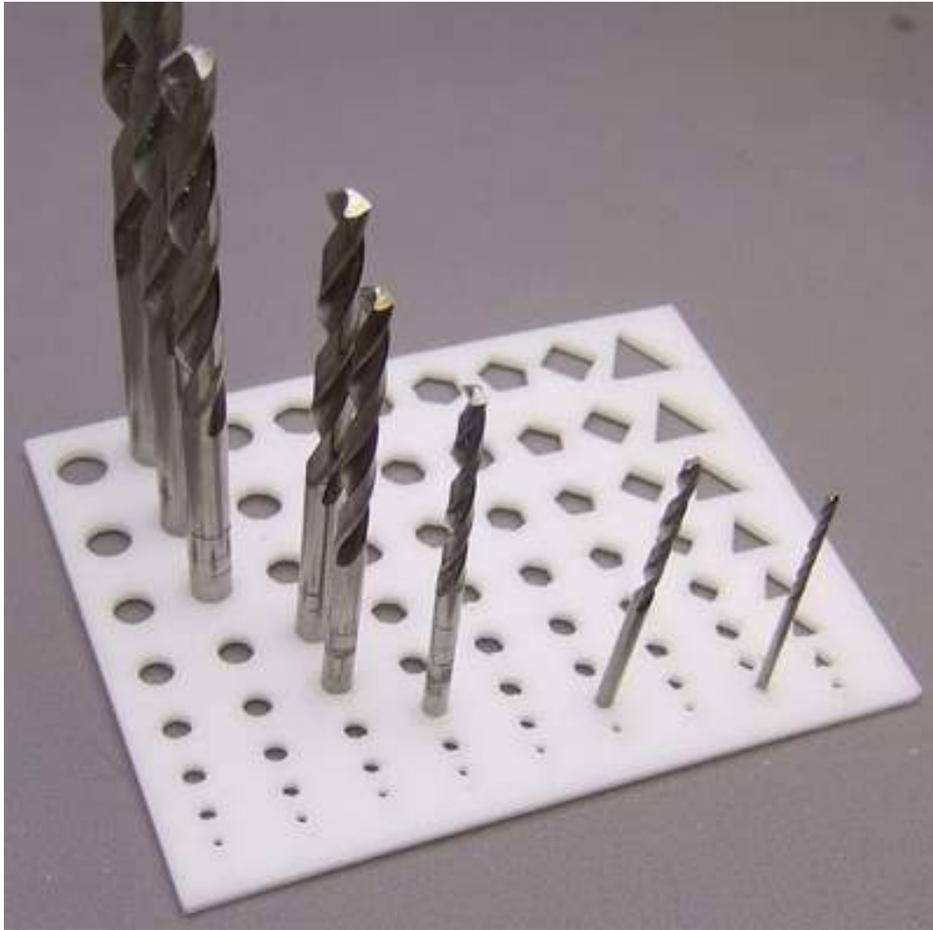
```

echo(v,shrink);          for(d = [1:9]) {          translate([d * d + 5 - ((v ==
3) ? 3 : 0), 13 * i, 0])          cylinder(h= 20, r = (d/2)/shrink, $fn= v);
          }          }          }}

```



I printed the resulting shape on HydraRaptor and used drill shanks to gauge the hole sizes. Not terribly accurate as the shanks tend to be a little smaller than the tip. I inserted the drills in the highest vertex count hole that it would fit in.



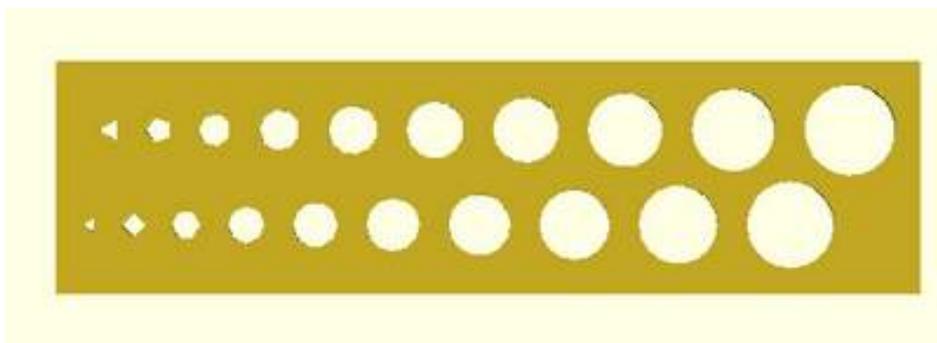
A pattern emerged that the seemed to indicate the maximum number of vertices you can have before the hole shrinks is twice the hole size in mm. The only drill I couldn't fit was the 1mm drill because you can't have a polygon with only two sides. The "1mm" triangular hole did at least leave a hole though, whereas higher polygon counts fill in completely.

To test this simple rule I made a new shape with holes from 1mm to 10.5mm in 0.5mm steps with the number of vertices set to twice the diameter and the diameter increased by  $\cos(\pi / n)$ .

```

module polyhole(h, d) {
  n = max(round(2 * d),3);
  rotate([0,0,180])
  cylinder(h = h, r
= (d / 2) / cos (180 / n), $fn = n);
difference() {
  cube(size = [100,27,3]);
  union() {
for(i = [1:10]) {
  translate([(i * i + i)/2 + 3 * i , 8,-1])
  polyhole(h =
5, d = i);
  assign(d = i + 0.5)
  translate([(d * d + d)/2
+ 3 * d, 19,-1])
  polyhole(h = 5, d = d);
}
}}

```



I found that all my drills bigger than 1mm fit. The large ones are a snug fit and the smaller ones a little loose, probably because with only a few tangential points touching there is little friction.



These two tests were done on HydraRaptor extruding 0.375mm filament from a 0.4mm nozzle. I printed this the test again on my Mendel with 0.6mm filament through a 0.5mm nozzle and the drills still fit, so it seems universal, at least amongst my machines. It would be interesting to see if others get the same result, so I have put the files on [Thingiverse](#).

My goal is to work out how to print circular holes the correct size, but this seems like a good hack for OpenScad designs to allow holes to come out the right size, regardless of the printer or whether it compensates hole diameters. For example, one would expect circular holes to come out right on a professional printer, so if you have oversized circular holes in your model they will come out too big. However, if you use these low vertex count polygonal holes they should still come out the right size as one would also expect a professional printer to print polygons at least as accurately.

# Spot on flow rate

Sunday, 13th March 2011 by Nophead

I have been doing some fine tuning of flow rate recently. I had previously noticed that PLA appears to need a slightly lower flow rate than ABS. I didn't notice this with HydraRaptor but I did when I changed from PLA to ABS on my Mendel, which has a Wade's extruder. My theory was that PLA feeds faster than ABS for the same rotational speed of the pinch wheel because, being much harder, it sits on the crests of the teeth and hence is driven by a larger effective pinch wheel diameter than ABS, which sinks in further. This effect is more extreme with a smaller pinch wheel. HydraRaptor has a 13mm pinch wheel compared to just 5mm for the hobbled bolt in my Wade's.

Other people have claimed that ABS changes density when it is extruded. I didn't believe that so I did an experiment to investigate.

I programmed HydraRaptor to extrude 100mm of ABS. I put a mark on the feedstock about 120mm away from the top of the extruder and measured how far the mark moved. I also measured the length and diameter of the extruded filament and I also weighed it and a 100mm sample of the feedstock. These are the results: -

Filament input to the extruder: 105mm of 2.98mm ABS equals  $732\text{mm}^3$ , weighs 0.777g, density  $1.06\text{ g/cm}^3$ .

Filament extruded: 2.89m at 0.56mm diameter equals  $712\text{mm}^3$ , weighed 0.764g, density  $1.07\text{ g/cm}^3$ .

So on the face of it the volume has gone down by 3% and the weight by 2% giving a slight increase in density. This could be explained by some volatile compounds boiling off, which they do, but I think it is mainly measurement error. In particular the diameter measurements have a big effect because of the square law for area. I took four measurements and averaged them but that is not many along 3m of extruded filament. Also the electronic scale I used to weigh the filament does not have a very stable display as it is only a cheap instrument. It is certainly a lot less than the 15% I have seen reported though.

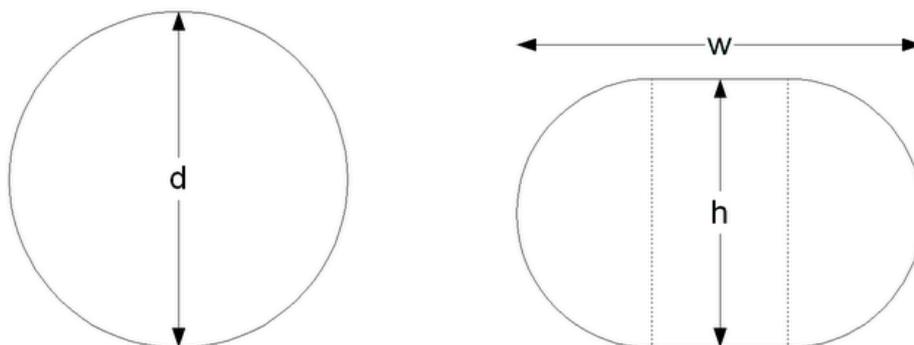
I also extruded "100mm" of PLA and that actually fed 110mm, showing that with a 13mm pinch wheel it feeds about 5% faster. With a 5mm hobbled bolt I would expect that to be about 12%, which starts to become very noticeable.

So I corrected the pinch wheel diameter in my software for the correct value for ABS and added a bodge factor for PLA. That left the flow rate a bit too low as it has previously been producing good looking objects with the overfeed, so I reviewed the maths I was using.

I have always extruded filament with a 1.5:1 width over height ratio and use a flow rate that would fill a circle 1.25 times the layer height. That was because I originally observed that you need to squash the filament to 0.8 times its diameter to get a good bond and that makes the width about

1.5 times the height. However, that only gives a packing density of 82%, which is a bit low. If you increase the flow rate so the infill is 100% then the outlines will be too wide. This is because the infill can occupy the full rectangular cross section of the filament road, but the outline, being unconstrained, will not have straight sides, so will be wider.

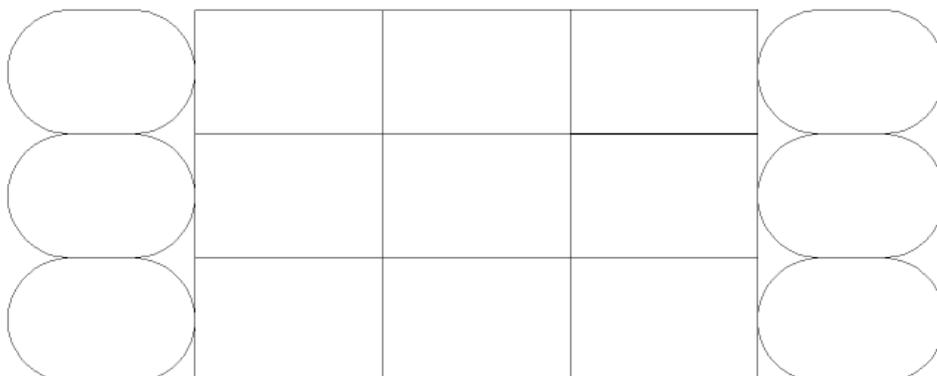
I reasoned that the outline will be extruded with a flat top and bottom where it is constrained between the nozzle and the bed but the sides will most likely be semicircular due to surface tension effects. This led me to a formula that gives the width from the notional extrudate diameter and the layer height.



Equating the two areas gives  $\frac{\pi d^2}{4} = \frac{\pi h^2}{4} + h(w - h)$ . So  $w = h + \frac{\pi}{4}(d^2 - h^2)$  allowing the width to be predicted from the layer height and the flow rate.

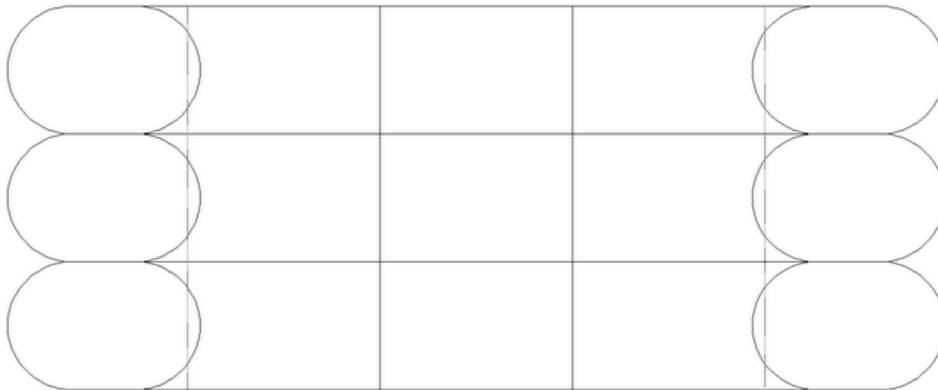
Calling the aspect ratio  $a = \frac{w}{h}$  and re-arranging to get the flow rate to make the desired width gives:  $d = h(1 + \frac{4}{\pi}(a - 1))$ . For an aspect ratio of 1.5  $d = 1.28h$ . I had previously been using 1.25h which is about 5% too low but was compensated for by the pinch wheel overfeed. I made a single walled box with the corrected pinch wheel diameter and the new formula and verified that the walls were 1.5 times the layer height.

I also used the same flow rate for the infill, but that can be increased up to the full area of the rectangle  $wh$ . Because the outline and infill use different flow rates there is a small deficit of plastic where they meet, as this model shows: -

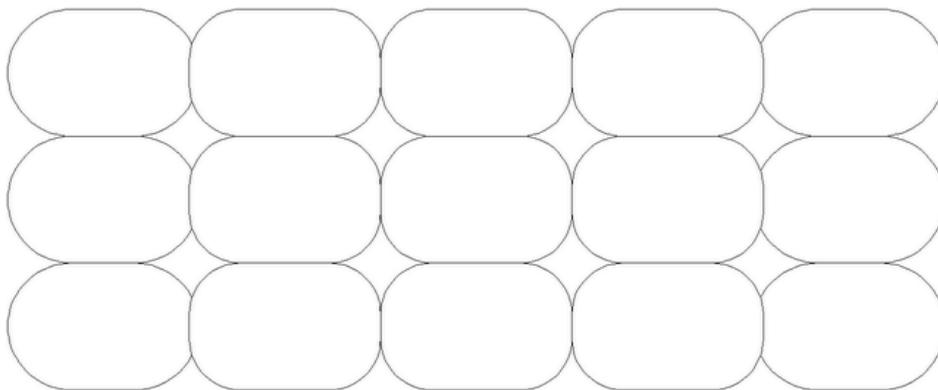


This can be fixed by using the infill perimeter overlap ratio setting in Skienforge, but how much? The deficit in area is a rectangle  $h^2$  minus a semicircle of diameter  $h$ , i.e.  $h^2 - \frac{\pi h^2}{8}$ . If the infill overlaps by a distance  $x$  then it contributes an area  $x \cdot h$ . Equating these gives  $x = h(0.5 - \frac{\pi}{8})$ .

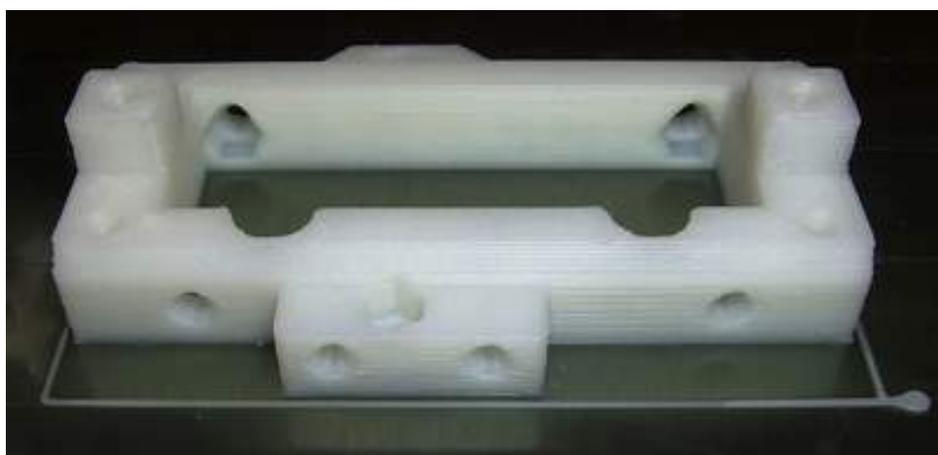
Converting to a ratio of  $w$  gives  $x/w = (0.5 - \pi / 8) / a$ . For  $a = 1.5$  that gives an overlap of 0.07 leading to a "fully stuffed" model where the solid layers are 100% plastic.



In practice that leaves no room for error and requires the nozzle to force the plastic into the corners of the rectangular channels like an injection molding machine. I found I get a better looking object with the volume reduced to 90% of that value. So for the infill I use the formula  $d = h(0.9 - 4a - p)$  giving  $d = 1.31h$  for  $a = 1.5$ , making the optimum flow rate for the infill about 5% more than the outline. I also use an overlap value of 0.05 giving the theoretical packing arrangement below.



Running the new equations on my Mendel certainly produces nice looking objects:



At least four people I have sold parts to have commented they look as good or better than parts they have seen from a commercial machine. I use filament about twice the diameter that commercial machines use, which results in more visible layers and rounded corners, etc, but apart

from that I must be close now.

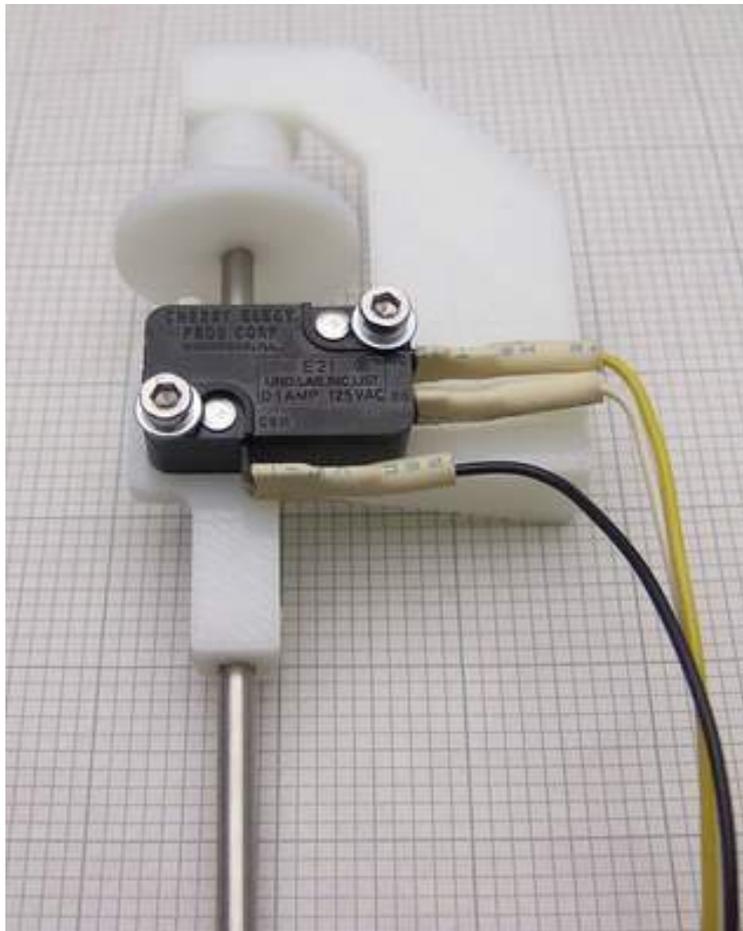
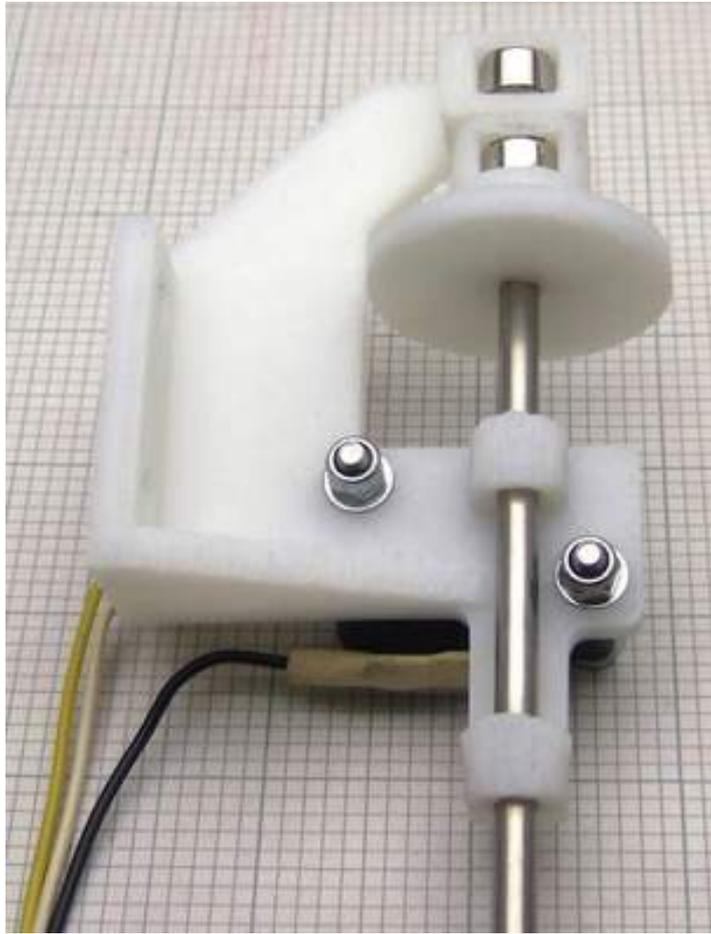
# Auto z-probe

Monday, 4th April 2011 by Nophead

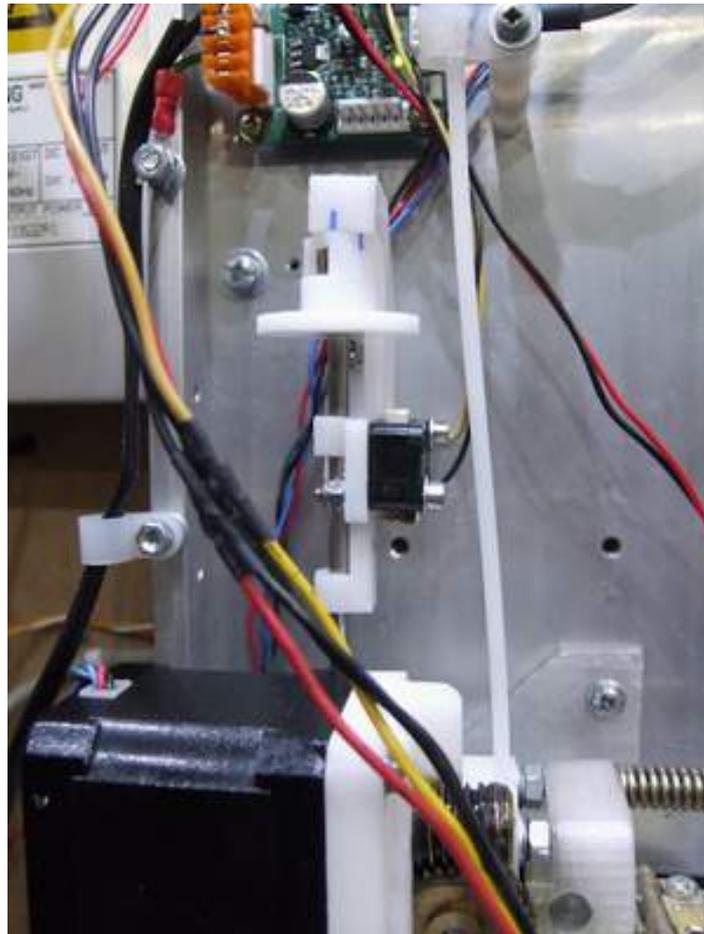
A niggling problem I have with Hydraraptor is that the z-axis calibration varies with the weather and how much it is used. This is because the frame is made from wood, which absorbs atmospheric moisture and expands. When the machine is running constantly the heat from the bed dries it out and it plateaus at a low z-value. If I don't use it for a while the z-axis gets higher by as much as 0.5mm in wet weather and the first few builds need large adjustments. When printing raft-less the initial layer height needs to be accurate to about 0.05mm for 0.3mm layers.

When it was configured as a milling machine I made a tool height sensor to solve the problem. It doesn't work for FFF though because the nozzle usually has hot plastic dribbling from it and it also wastes some of the build area.

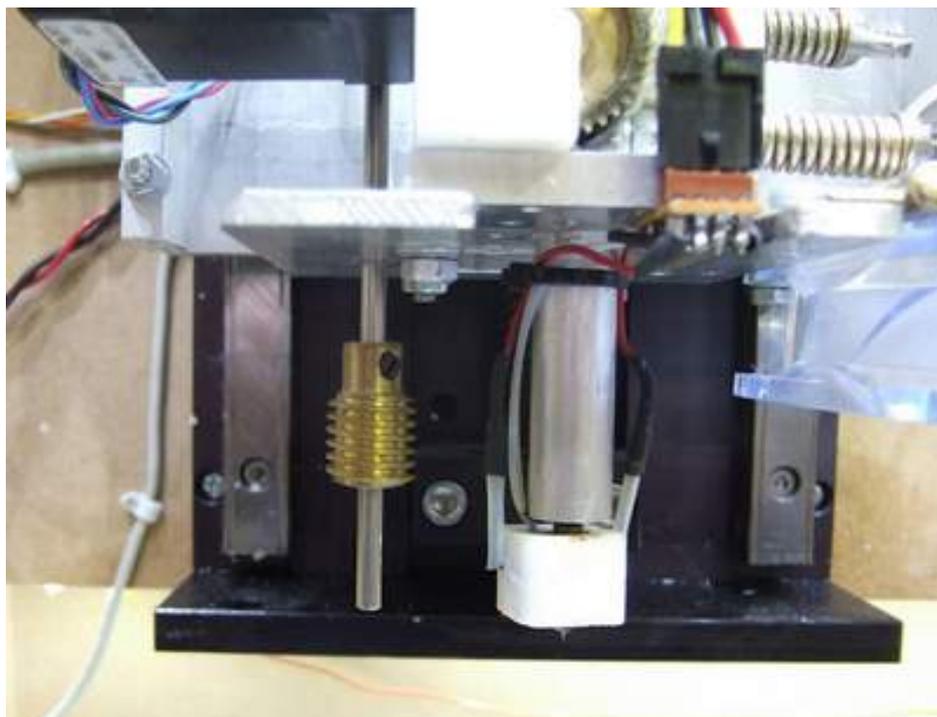
To solve the problem I designed a z-probe that hangs below the nozzle at the start of the build but then retracts itself after the measurement. It consists of a weighted metal rod that slides through a couple of plastic guides. It has a plastic flange on the top that depresses the plunger of a light action micro switch. In measurement mode the rod protrudes about 10mm below the nozzle. When the measurement is completed the axis descends to place the nozzle close to the bed. The rod lifts until the attractive force of two Neodymium magnets causes it to be pulled about 5mm above the nozzle and held there until the start of the next build.



Here it is installed on the axis.



I used a Meccano worm gear as an improvised weight to ensure the micro switch is activated, much cheaper options exist! The actual weight is surprisingly not very critical. It must be enough to activate the switch reliably but not too heavy for the magnets to lift.



The operating procedure is as follows: The machine warms up the bed and the extruder and waits for a couple of minutes for the nylon pillars that support the bed to expand fully. It then extrudes a length of filament with the z-axis at the top and gives an audio prompt on my computer. I grab the filament and snap it off and then lower the z-probe, which closes the switch and instructs the machine to start.

The axis descends rapidly to place the rod 1mm above the centre of the bed. It then descends in 0.1mm steps until the switch opens. Then it ascends in 0.01mm steps until the switch closes again and that gives the Z calibration point, which is a known distance (about 10mm) above the bed. The nozzle then descends to 1mm above the bed to retract the probe before it moves to the start point.

Here is a video of the sequence.

It could also lower the probe automatically simply by having a bracket near the top of the z-axis to catch the flange as the axis rises past it. The reason I don't do that at the moment is because I use the act of manually lowering the probe as a cue to the machine that I have removed the start extrusion.

The design is on [Thingiverse](#).

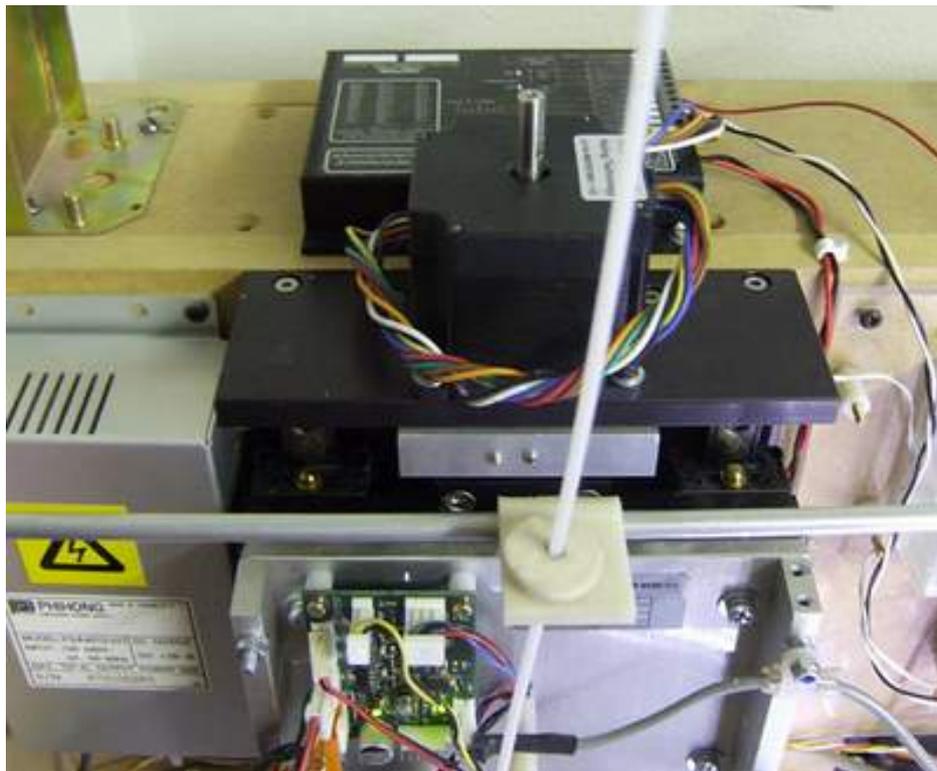
# Auto bed leveling

Monday, 25th April 2011 by Nophead

One thing I find tedious is leveling the bed of my machines, so I decided to make use of the Z-probe on HydraRaptor to measure the incline of the bed and compensate for it in software.

First I had to increase the resolution of my Z axis. When I first built the machine I did not realise that I would need fine resolution on Z, so I used an old 24V unipolar motor that I had in my junk collection. With half stepping it gave me 0.05mm resolution. I thought that it was a 200 step motor and that the lead screw had a pitch of 20mm. It turns out it must have been a 250 step motor because the pitch is actually 25mm. I replaced it with a Keling KL23H251-24-8B NEMA23 left over from my Darwin and I now drive it with a x10 microstepping controller the same as I use on X and Y. That gives me a resolution of 0.0125mm and also makes it the fastest axis on my machine. It can easily do 150 mm/s but seeing the nozzle approaching the bed at that speed and then stopping within 0.3mm is very unnerving, so I limit the speed to 50mm/s!

I no longer need the heat sink and fan because the new motor is more efficient and is directly mounted on the axis, which takes the heat away.



I use 6mm aluminium tooling plate so I make the assumption that the bed is a flat plane (rotated slightly around the X and Y axes and offset a little in Z). That means I only need to measure the height at three arbitrary points in order to characterise that plane. I then use the method here to calculate the equation of the plane in the form  $ax + by + cz + d = 0$ . The method puts two vectors through the three points and takes the cross product to get a vector at right

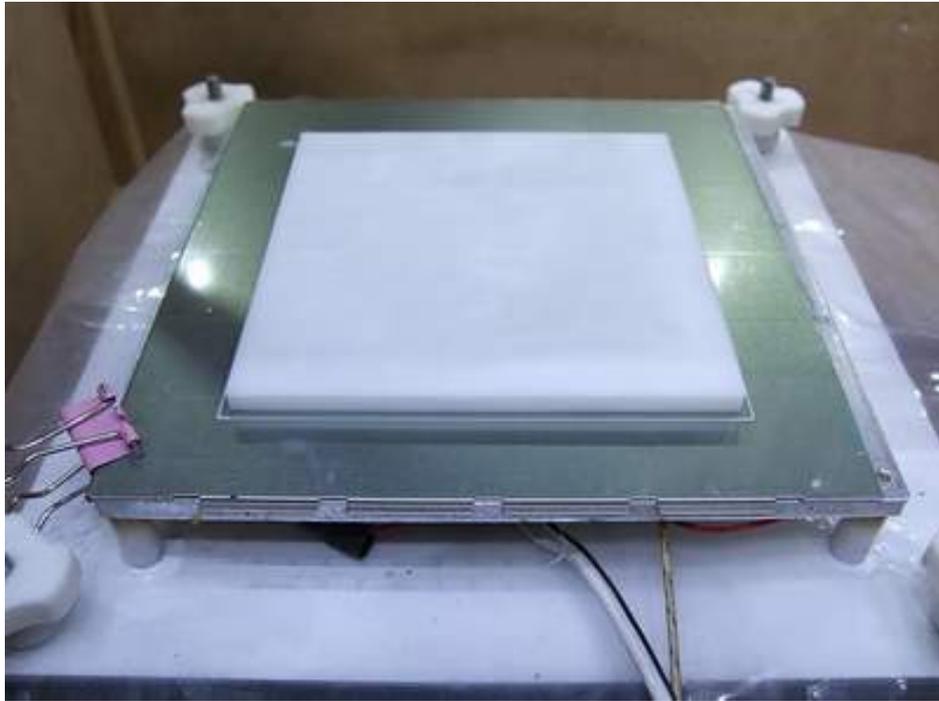
angles to both of them. That is the normal to the plane and its components are the coefficients a, b and c. Substituting the first point into the equation gives d.

It is important that the three points are ordered anti-clockwise, otherwise the normal vector would point downwards and the machine would try to build the object upside down under the surface of the bed!

Given the bed's plane I then have to make the model coordinates relative to that inclined plane and transform them to the coordinate system of the machine. To do that I calculate two orthonormal basis vectors on the plane using it's equation and use the normalised normal vector for the third. I then multiply the model coordinates by those vectors and add the origin to find where they are in the machine's coordinates. Here is the Python code I used: -

```
class Plane:      "A plane in 3D."      def __init__(self, p0, p1, p2):      "Construct from three
anti-clockwise points"      #      # Calculate the normal vector      #      v1 =
p1.minus(p0)      v2 = p2.minus(p0)      normal = v1.cross(v2)      if normal.z < 0:
    raise Exception, "Probe points must be anti-clockwise"      #      # Coefficients of the
plane equation ax + by + cz + d = 0      #      a = normal.x      b = normal.y      c =
normal.z      d = -a * p0.x -b * p0.y -c * p0.z      #      # Generate three basis vectors
aligned with the plane      #      self.origin = vector( 0, 0, -d / c)      self.k = normal
        # k axis is simply the normalised normal      self.k.normalize()      px =
vector( 1.0, 0.0, -(a + d) / c) # an arbitrary point on the x axis: x = 1, y = 0      self.i =
px.minus(self.origin)      # find direction to it from origin      self.i.normalize()
        # make a unit vector      self.j = self.k.cross(self.i)      # make a third vector
mutually at right angles to the other two      self.j.normalize()      # make a
unit vector, probably is already      def transform(self, p):      "Transform a point to be
relative to the plane"      return
self.origin.plus(self.i.times(p.x)).plus(self.j.times(p.y)).plus(self.k.times(p.z))
```

To test the principal I put a 1mm thick washer under one corner support of the bed to give it an extreme slant compared to normal misalignment. I then built a 100 x 100 x 5mm cube with 0.35mm layers. This would normally be impossible without the bed being level to a small proportion of the layer height. The result was that it came out fine.



As the nozzle traverses the object in XY the Z axis moves a few microsteps. It is barely visible but I can hear it and feel it if I hold the stepper motor shaft. The object is built perpendicular to the plane of the bed, so the sides are very slightly slanted with respect to the machine axis and the nozzle. I am not sure how well it would work on Mendel as the z-axis is geared down so much. It would probably still work as the movement required is so small when the bed is reasonably level. I can't test it as there isn't room for a z-probe on my carriage due to the large heat sink.

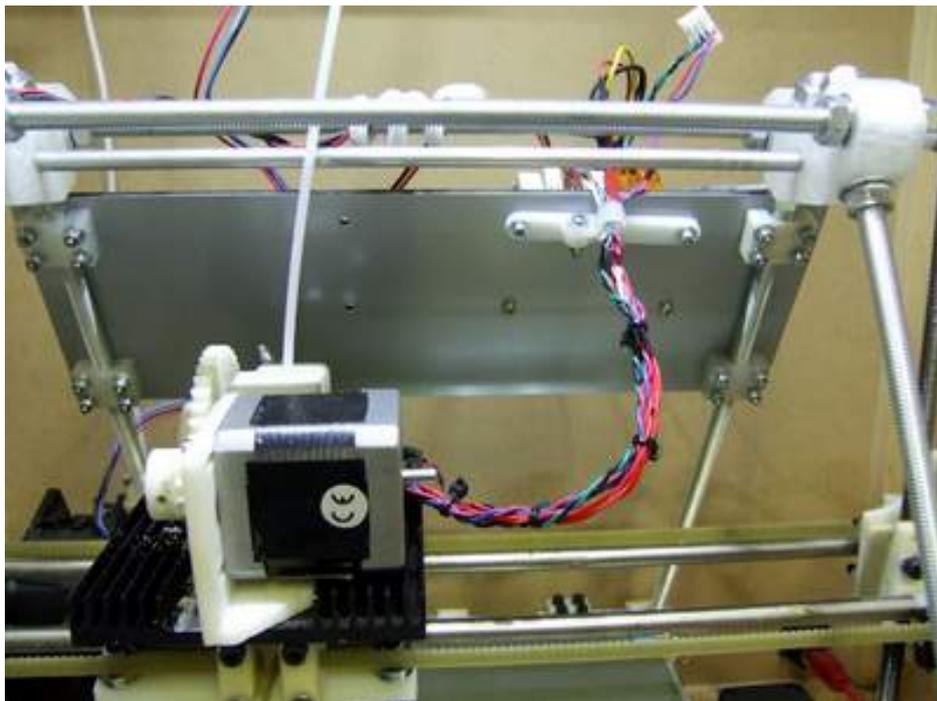
# Reliable connections

Thursday, 9th June 2011 by Nophead

After eliminating lots of other sources of unreliability in my machines, electrical connection failures are now the most common failure mode.

The latest failure on my Mendel was that it started leaving a 10mm gap in the outline rectangle that it draws around the objects. Since a bed full of objects still seemed to build OK I decided perhaps it was due to an air bubble in the extruder while it was warming up. However, one time I saw the extruder motor stall and realised it was actually a bad connection.

I have come to realise that simple friction fit connectors do not work in the environment of these machines. I tried re-seating the motor plug but that did not fix it, so I figured the cable must be faulty. I wired both coils in series to my multimeter and waggled the cable until it went open circuit. That allowed me to locate the break and it was, as could be expected, at the point where the cable bends the most, i.e. just below the cable clamp on the top right of this picture: -



On reflection this was not a good arrangement as the cable is only just long enough for the extremes of travel, so it is forced to bend sharply both ways at the clamp. After millions of movements the strands break one by one but the insulation holds the ends together making it only lose contact when it is stretched. When I pulled the ends of the wires three of them snapped very easily, indicating most if not all the strands were broken.

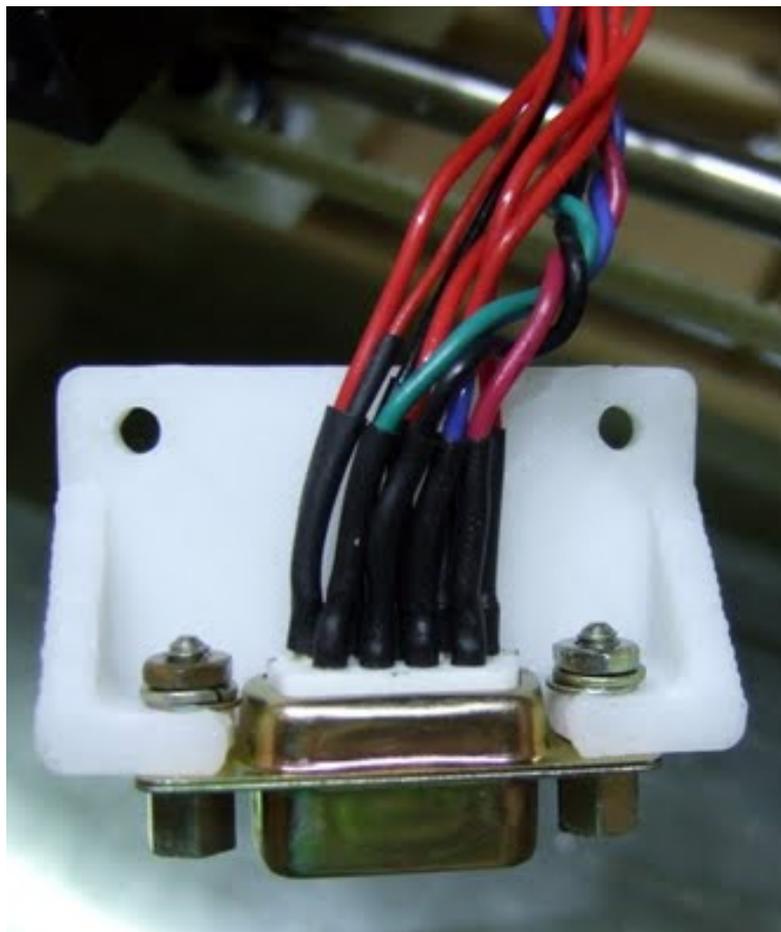
I had a similar problem with the mains wire to a heated bed a while ago. In that case the arcing melted the insulation and allowed the live and neutral to short out, blowing a hole in outer sheath

of the cable. Not good! Normally you expect a fuse to protect against a cable fire, but if all the strands start breaking, reducing the current capability, or it breaks and arcs, the fuse offers no protection against fire. Even a low voltage heated bed could fail in this way because of the high current.

The XY table of HydraRaptor uses 9 way D-type connectors. These have been totally reliable moving connections because they are screwed together and have gold plated pins and proper strain relief. The professional stepper motor drives on HydraRaptor have screw terminal blocks for their connections, and again they have proved totally reliable. In contrast all the friction fit connectors fail if there is any movement or vibration of the wire. Some even burn out despite being run at well below their current rating. The contact resistance rises and they then start to heat up.

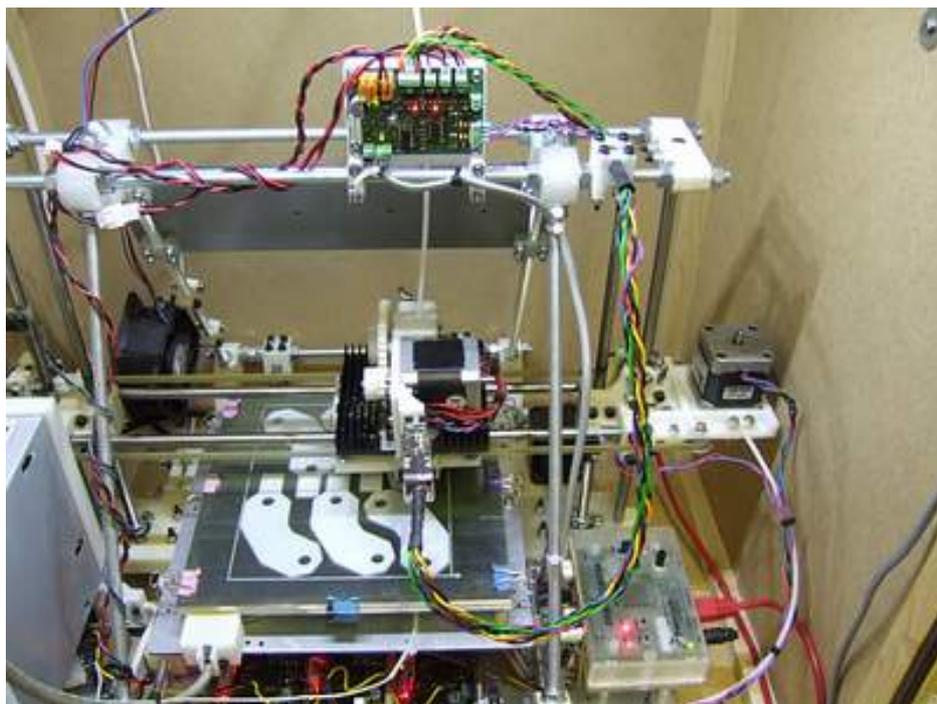
I rewired my Mendel extruder using a 9 way D-type at the extruder and a longer loop of cable. That necessitated resiting the extruder controller and I also replaced all of its 0.1" MTA connectors with screw terminal blocks. The wires could go straight into these but I added ferrules to allow them to be more easily removed and replaced. I just push the wire into the ferrule and then squeeze it with pliers.

I rewrapped a bracket to attach the DB9 connector to the back of Wade's extruder bracket.



The pins are four motor connections, two heater, two thermistor and one heatsink fan that shares a 12V feed with the heater.

Here is the new arrangement :-



The cable loop is much longer, so it bends through a much smaller angle. The top end goes through two cable clamps before it goes to the extruder controller. I found that if you put a bunch of wires through a single clamp you can get some movement at the other side of the clamp. Using two eliminates any movement of the wire relative to the board, less critical now I that have screw terminals, but still a good idea.

It should last a lot longer than the previous cable (which lasted for 15 months of continuous use) and can be easily replaced. I have seen people use corrugated tubing to protect the cable, but I didn't fancy adding any more drag on the extruder as it would increase backlash.

Interestingly, although my extruder stepper motor connections have failed several times, I have never damaged the Allegro driver chips.

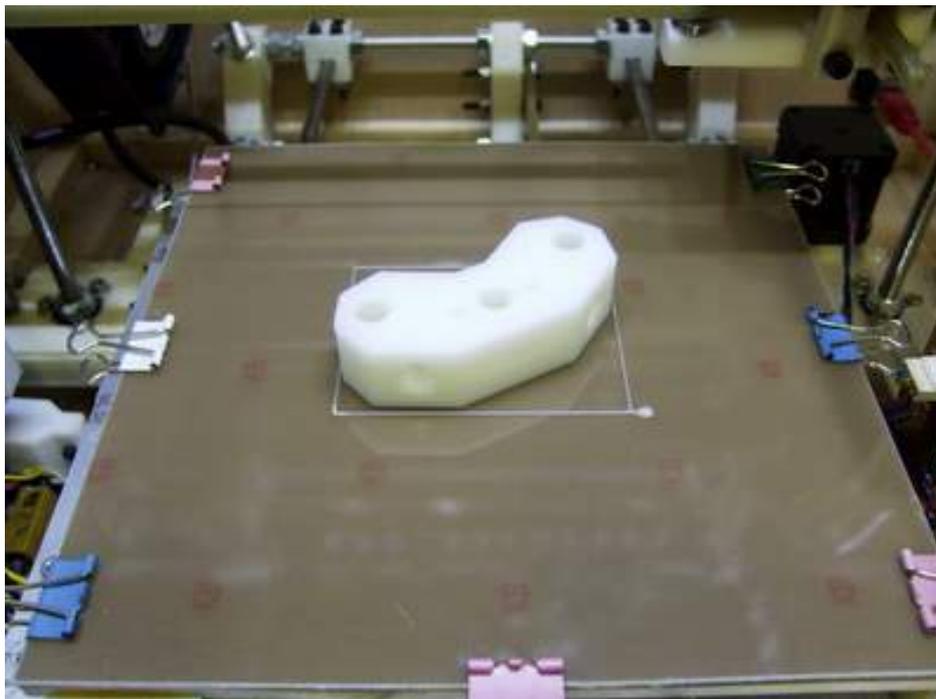
# ABS on FR4

Friday, 10th June 2011 by Nophead

I have been printing both ABS and PLA on PET tape for more than a year now. It works well and lasts for many months, but eventually the silicone adhesive fails and it blisters. Applying it is fiddly to avoid any overlap but also not leave gaps between the adjacent runs of tape. I have been on the lookout for a solid material to avoid these pitfalls.

Stoffel15 ([Wolfgang](#)) told me that [FR4](#) fibreglass PCB material works well. FR4 is the most common PCB material and is a glass fibre and epoxy resin laminate. It will handle solder re-flow temperatures (~ 240°C) for short durations and can be used continuously at 140°C. As I haven't worked on single sided PCBs for many years, I had forgotten what the surface of the raw material looks like. It is actually smooth and glassy, so ideal as a bed material.

I ordered some single sided PCB material from [Farnell](#). It works fantastically well. It seems to have a bit more grip than PET and has the advantage that there are no lines on the part from the joins in the tape. It also has no give in it, so I don't get any blistering at sharp corners like I did with tape, sometimes leaving shallow dimples.

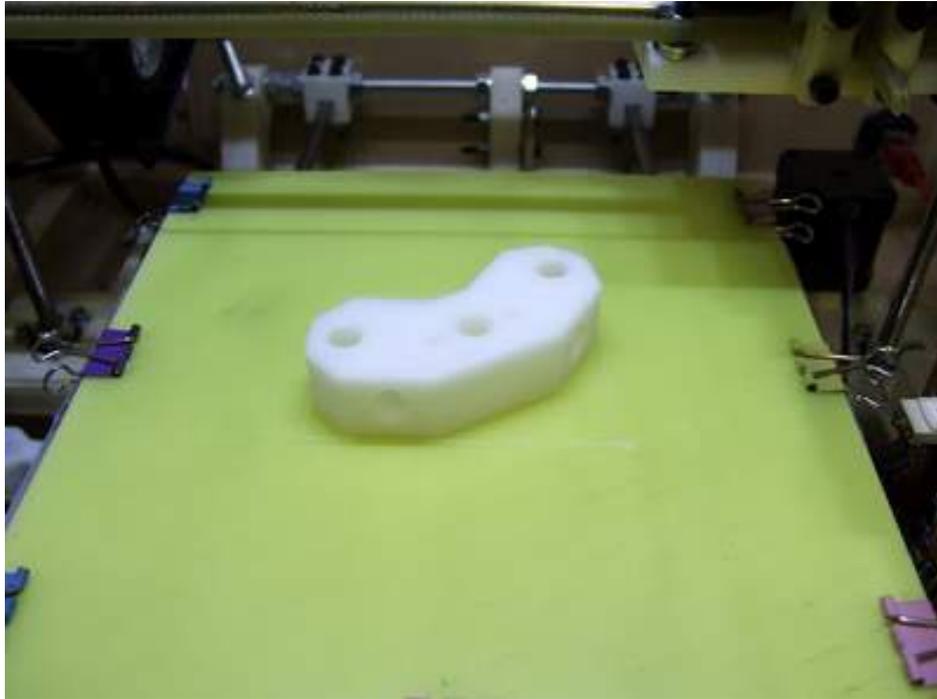


Another advantage is that when the object cools it tends to break free because it contracts more than the bed does. With tape there is some compliance, so it usually stays stuck when the object cools and it is often hard to remove parts. With FR4, if you get the layer height spot on, the parts break free of their own accord, and if not, are very easy to snap off. This vertex bracket was loose after the bed cooled to 50°C.

Yet another advantage is that I stick the tape to a steel plate 0.9mm thick that weighs 280g. The

FR4 is 1.6mm thick but it only weighs 134g, so less than half the mass.

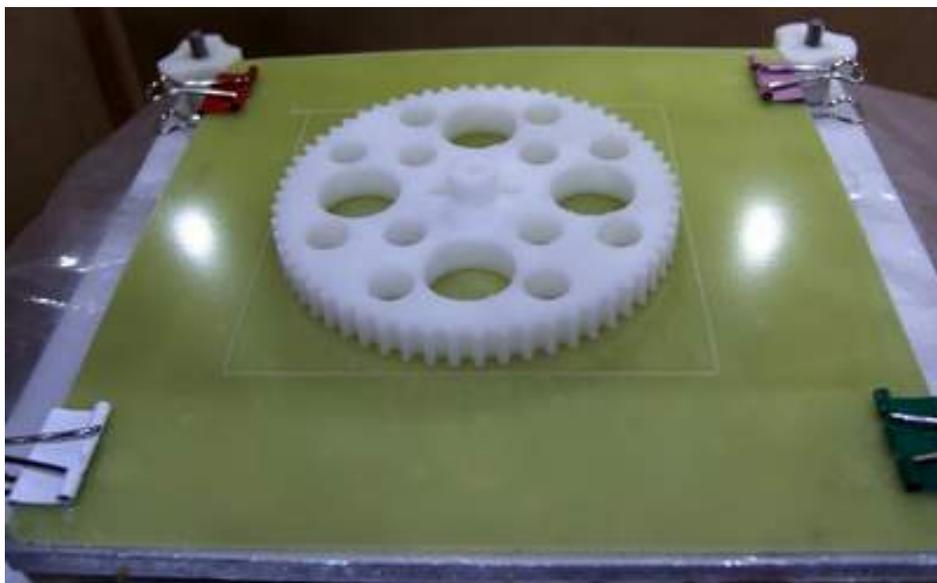
I also tried some plain FR4 without copper and that seems to work just as well. It is 0.9mm thick and weighs only 75g. The disadvantage is it is bright yellow, which makes it hard to see the white plastic on it.



I have printed a full set of Mendel parts so far on FR4 and every part has come out perfectly flat, and was easy to remove.

I don't know if it will degrade over time, but there is no sign of surface damage so far. The dark features on the picture above are marks on the aluminium plate underneath.

The nice thing about the z - probe I have on HydraRaptor is that I can change the bed without any calibration.



This is what the underside of an object looks like.



I used the same temperature I used for PET tape, which is 140°C for the first layer and 110°C after that.

I haven't tried PLA yet, but my guess is it will stick because it seems to stick to a superset of things ABS sticks to.

Great tip Wolfgang!

In the past I tried FR2 (SRBP, Paxolin) but that did not work, probably because it had a matt surface. I also tried some CAT7FR, which is another type fibreglass PCB material, but again it had a matt surface and did not work very well. I was able to build a flat object on it, but the first layer outline did not stick properly, so some holes were a bit scrappy.

The copper on the bottom of the single sided material could be used as a heater like the [Prusajr heated bed](#) design.

# FR4 fail

Tuesday, 14th June 2011 by Nophead

Well it seems that FR4 only lasts for about a week. The grip slowly fades making the parts very easy to remove. In fact they all pop off as the bed cools below 60°C and slide about due to the fan and the bed's final movement to the front. The odd small part falls down inside the machine.

If I mounted my machine so it was inclined at 45° they would all fall out the front and could be directed by a chute into a hopper and the machine could then build continuously unattended. Who needs a conveyor belt! The only problem is the grip is now not enough to hold the bigger parts during the build.

I have tried cleaning with acetone but it doesn't seem to help. I suspect the high temperature is making the epoxy more brittle and less sticky. I will be able to prove that when the FR4 without copper on HydraRaptor fails. If I then turn it upside down and it still works on the under side then it is not a temperature ageing effect. If the other side is still working then it must be a reaction to the ABS or the acetone that is the problem.

It is shame because I much prefer a solid substrate to tape. Something like polyimide and fibreglass laminate would probably be ideal but it is hundreds of dollars for a piece big enough.

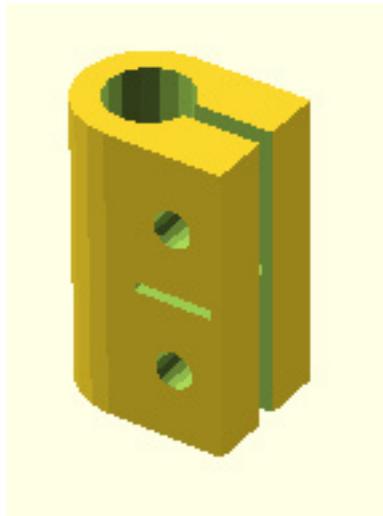
Wolfgang has posted a mystery material to me that sounds promising, so back to PET tape until it arrives. My friend Tony found that Farnell sells it in wider rolls. It seems to be a bit thicker as well, so is easier to apply, but a lot more expensive than the stuff from BestOfferBuy.com.

# Yet another Prusa Z-coupling

Saturday, 25th June 2011 by Nophead

I finally got around to building the Holiday Prusa Mendel I printed over Christmas. I had a few problems with some of the comedy parts and had to revert to using some of the more up to date ones that I sell.

I didn't find the Z couplings worked very well. The requirements are to couple the M8 threaded rod to the 5mm motor shaft exactly coaxially and with no vertical play, but with some angular flexibility to cater for slightly bent threaded rods or any slight angular misalignment.



The rods are not held very coaxially because the clamp is not symmetrical. The alignment depends on how much the two independent clamps are squeezed, which depends on the exact diameter of the shafts relative to the printed diameter of the part.

They are not very flexible either because they have to be strong enough to support half the weight of the X-axis and the extruder. The direction of pull is in the weak direction of the part that tends to de-laminate it, consequently I print them 100% fill to make them strong enough. I would imagine that if there is any wobble in them the constant flexing would eventually fatigue the part and cause it to break.

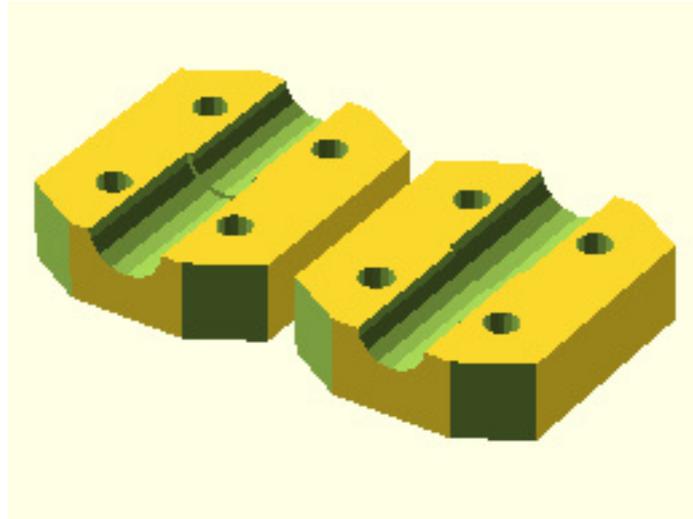
I looked around at the various attempts to improve these, but I wasn't happy that any satisfied all the requirements above. I did find two sources of inspiration though:

This one by keegi uses a piece of tubing to provide the angular flexibility and it also helps to grip the smooth motor shaft.

This one by Griffin\_Nicoll has the strong direction of the part in the right direction, but suffers the same problem as the original because it has two independent clamps. That is easily solved by removing the split in the top section, but then it would be difficult to grip the smooth motor shaft

without the clamp halves being exactly parallel, which would depend on the exact shaft and part sizes. It also has no obvious flexibility. Putting the tubing on the motor shaft solves both these problems.

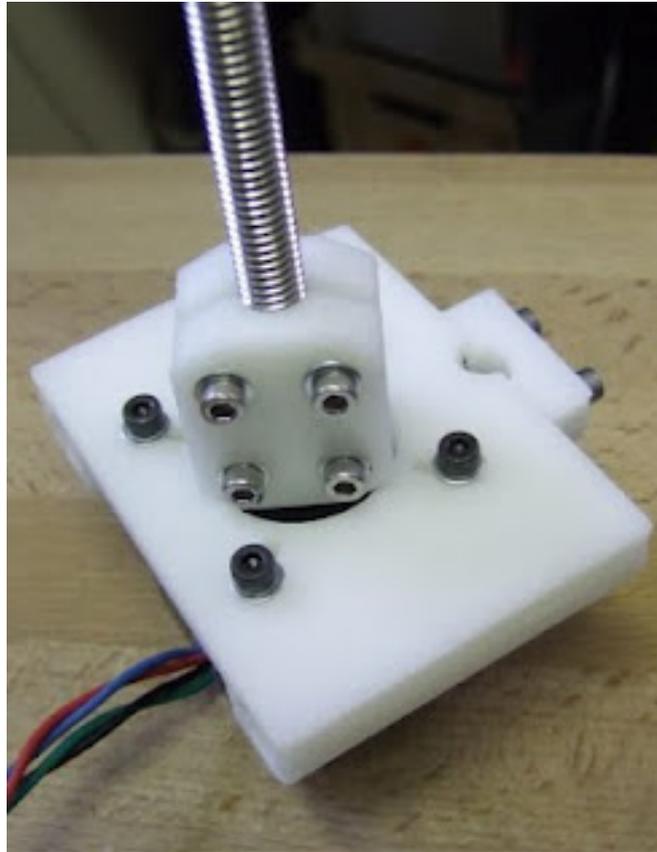
I hacked Griffin's script to make this version: -



I removed the split, changed the holes and the nut traps to fit M3 and changed the motor shaft diameter to 7mm, which is for a 5mm shaft with tubing on it.



Here it is mounted: -



Both halves are identical inside so not matter what the shaft size is they will always centre and align the shafts automatically. The sleeving allows the shaft to flex angularly and also makes a very firm grip on the motor shaft. The part bears weight along its strong direction and is not required to flex at all, so should last forever. Another possible benefit is if the part is made from PLA it is somewhat insulated from the motor shaft by the tubing, so there is less chance it will melt.

I haven't run the axis yet, but it turns very easily manually and there is no wobble at all. I will include these in my kits from now on and I will include the short piece of tubing as it would be annoying to have to buy just 30mm. Note it does require four extra M3x20 bolts, nuts and associated washers.

The files are [here on Thingiverse](#).

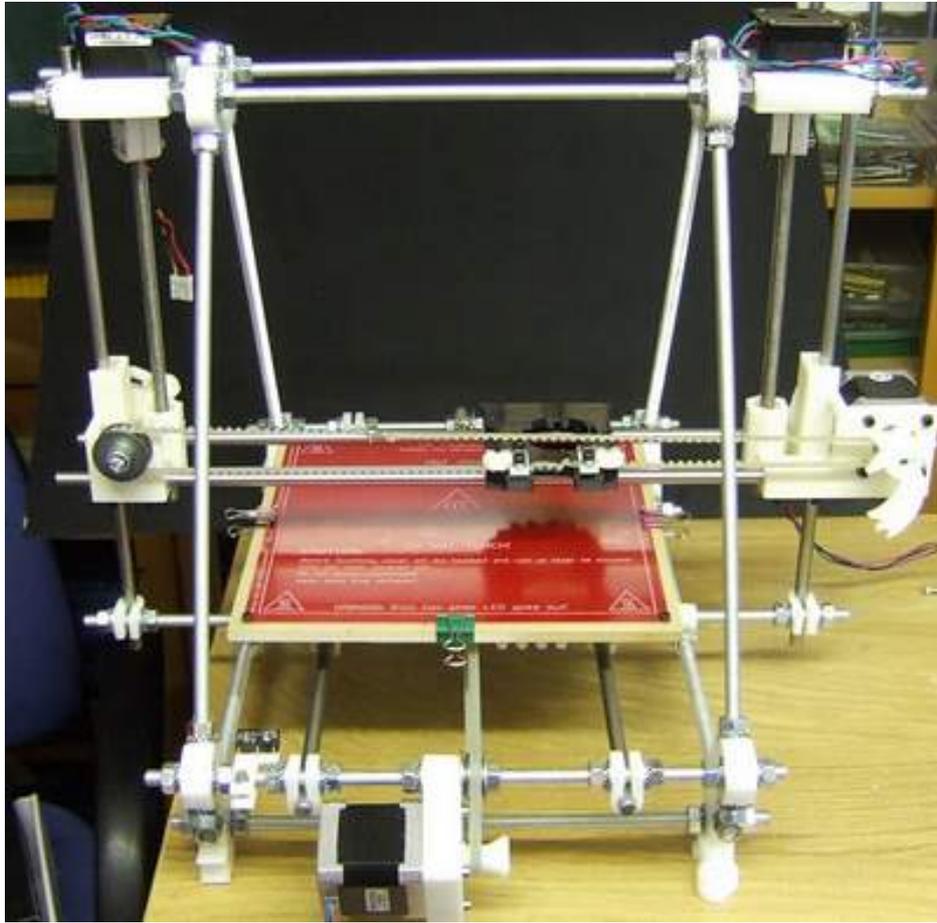
# Half belt hack

Sunday, 26th June 2011 by Nophead

I found that I didn't have enough belt to complete the x-axis of my Prusa, but I did have a couple of offcuts about half the required length. Since less than half the belt actually passes over the motor pulley I simply joined them in the middle. My first idea was to print a two part clamp. Another idea was to use heat shrink sleeving, but in the end I simply tied them with some wire.



I joined them back to back so that the teeth mesh, keying them together. This has the beneficial side effect that the smooth part of the belt goes round the smooth idler pulley.



It might actually be worth doing this to get smoother running, even if you do have a belt long enough. Also if you are on a tight budget the second half does not need to be toothed belt at all. It could be packaging strapping or steel wire, etc.

# Mendel90

Sunday, 25th December 2011 by Nophead

I never understood why Mendel has a triangular prism frame. The way I see it, the frame only has two functions: - To hold the Y bars in a flat plane and to support the tops of the Z bars. It isn't good at doing either:

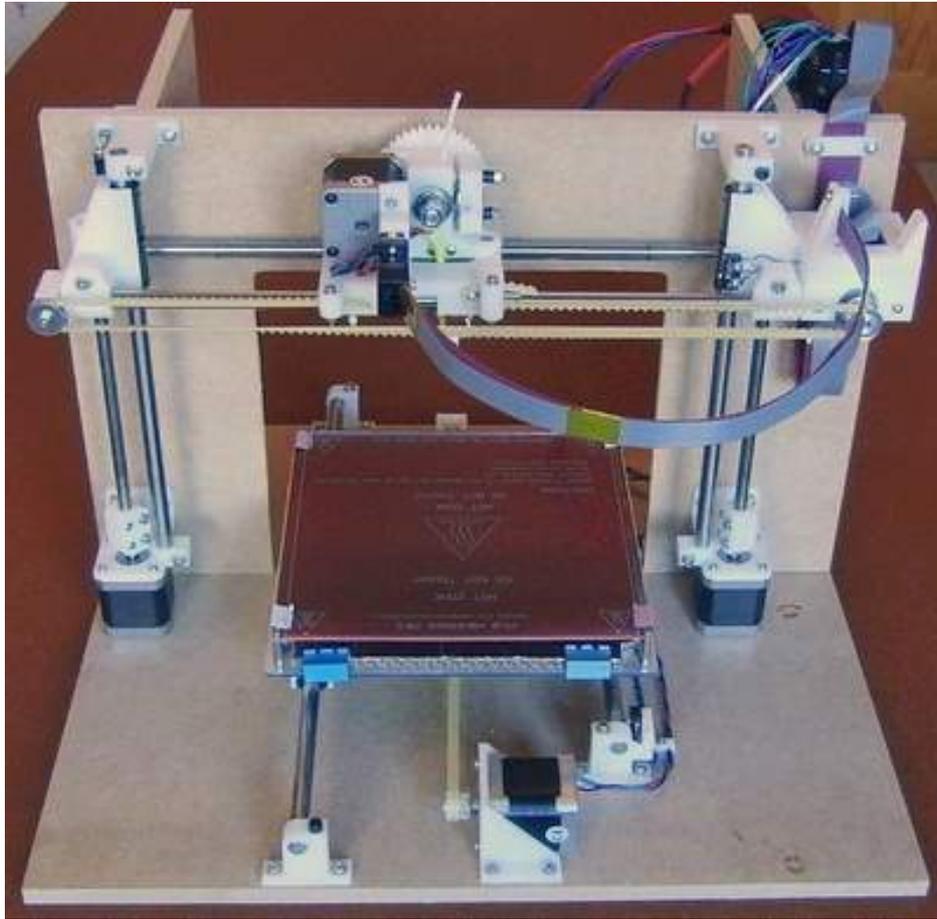
- The main forces on the Z bars are in the direction of the X-axis and the frame has no strength in that direction. It wobbles when the X-carriage changes direction.
- It also doesn't ensure the Y bars are in a flat plane because there is nothing to ensure one end triangle is not rotated slightly relative to the other.

After a trip down a cobbled street in Sheffield my Mendel behaves as if one corner of the bed is lower than the other three. This is impossible because it has a flat sheet of glass on it, but it isn't obvious what needs to be adjusted to fix it but it must be the ends of the Y -bars. The bed needs to be level to within about 0.05mm for good results printing 0.3mm layers without a raft. That is difficult to achieve when the Y axis is strung from bars at opposite sides of the machine.

Other problems are: -

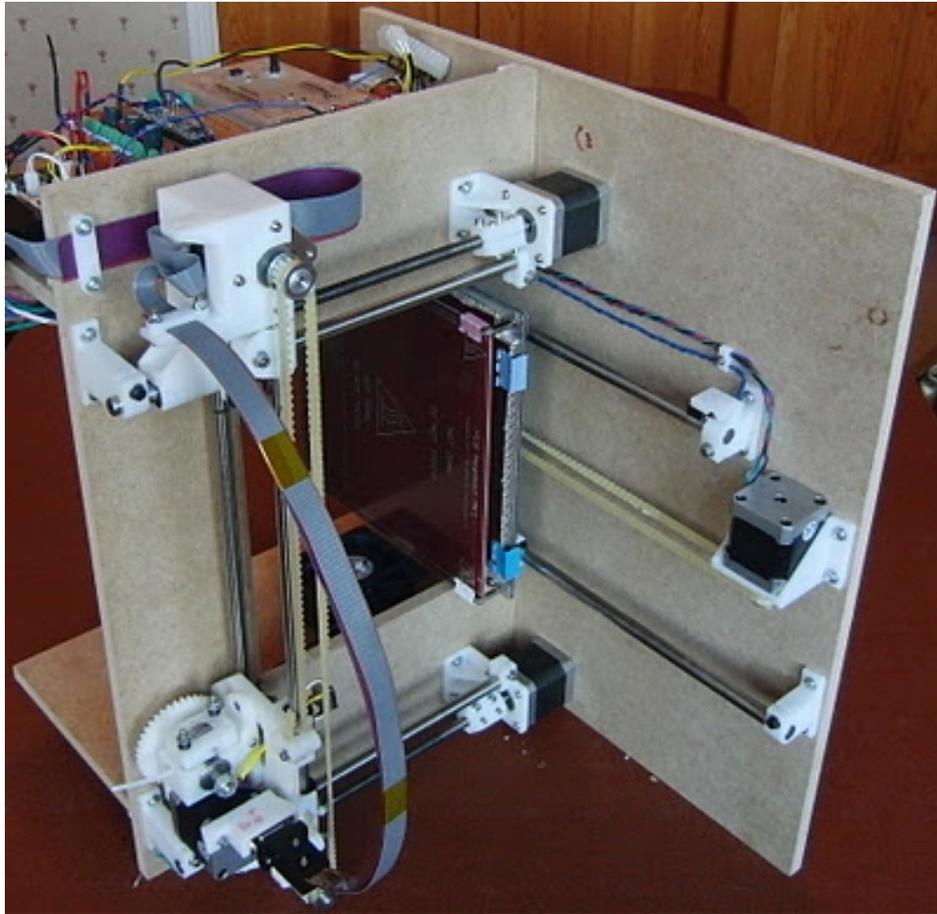
- It gets smaller at the top, so the maximum Z travel is limited by the extruder colliding with the bars.
- The sizes of the Z axis and the Y axis are tied together, so you can't change one without the other.
- It is difficult to adjust the axes so that they are orthogonal to each other and keep them that way if the machine is moved.

This machine is my attempt answer to these problems. I am calling it Mendel90 as I can't think of a better name at the moment. The 90 is to emphasise that the frame is based on right angles rather than 60 degree triangles.

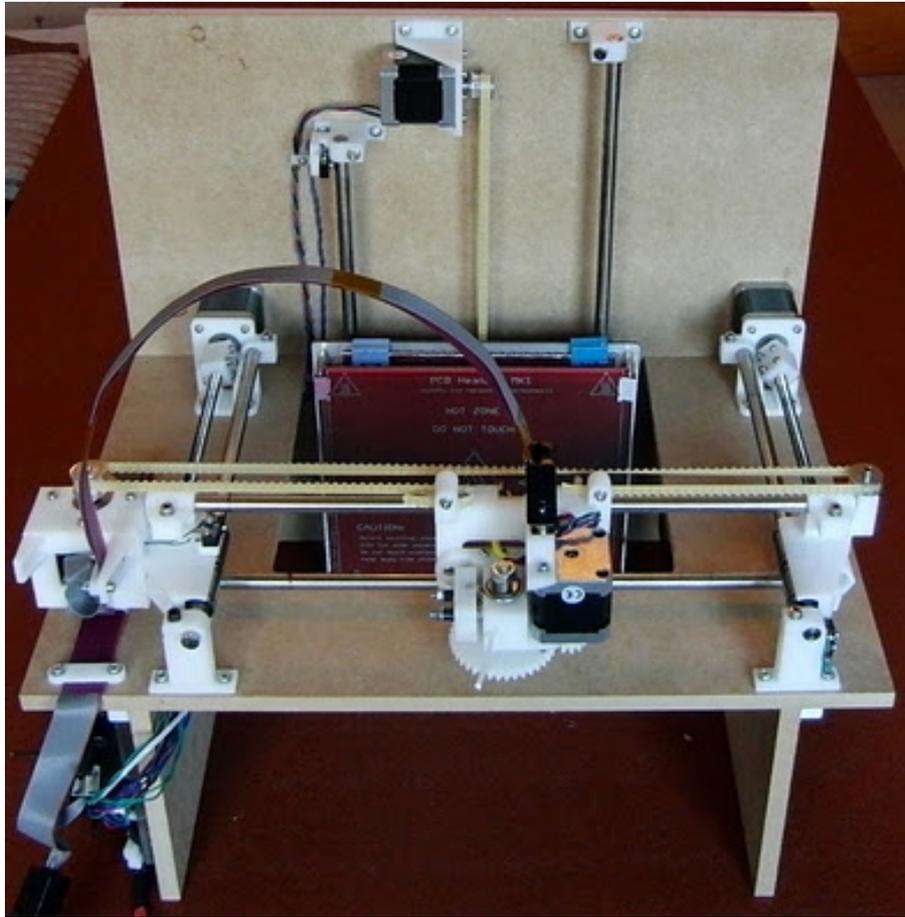


Two flat sheets are mounted at right angles to form the XY and XZ planes. Two buttresses maintain them at right angles to each other. This relies on the sheets being cut at perfect right angles but in the UK you can buy sheet materials such as MDF or acrylic cut to size and they have good right angles. The only cutting I had to do was to cut the arch out with a jig saw. It doesn't need to be accurate and it could be done with a hand saw. The piece removed could be used to make the Y carriage, depending on the material.

The buttresses are bigger than they need to be. I took them all the way back to give me plenty of room to mount my non-standard electronics, but it also has the advantage that the machine will sit on five of the six faces, making it easy to work on.



If the anti-backlash springs are fitted to the Z-axis it should print in all those orientations as well, which would be interesting to try. When printing directly on glass, parts come loose when the bed cools. If the machine was on its back they would fall out the bottom. Who needs an ABP? It might also solve the PLA ooze during warm up problem.



The gantry could be unscrewed and laid on its back over the top of the Y axis to make the machine more compact for travelling. In this case the buttresses could be slimmer to allow it to become even more compact.

I used B&Q style fixing blocks to fasten the sheets together.

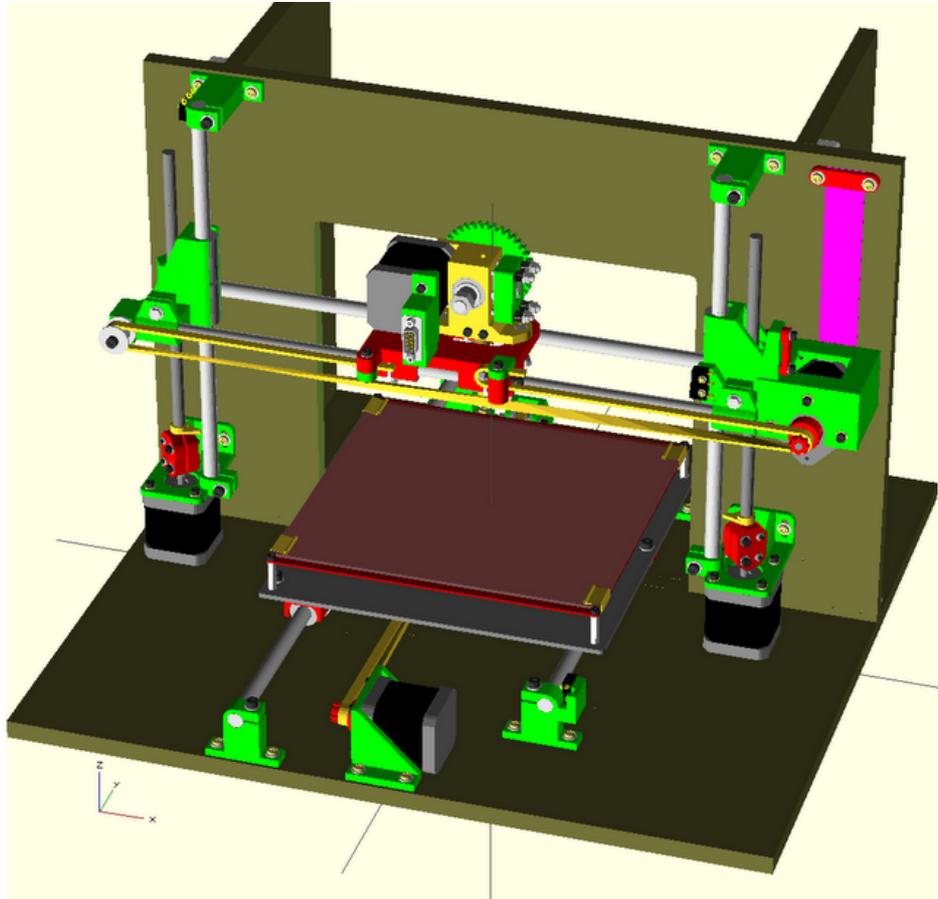


I bought some of these and I printed some. They are a lot faster to print than Mendel frame vertexes! The economics are interesting: they are cheaper to print than buy, but while my machines are fully occupied making parts to sell, it is more economical for me to buy them. The printed ones are actually more accurate than the injection moulded ones! The holes are all over the place. I think they must be formed by removable cores and the tool must be worn allowing them to move.

I drilled pilot holes using a paper template. I did this by exporting DXF files of the sheets from OpenScad. I then hacked together a Python DXF reader and an SVG writer to make a program that generated drill centres. I printed them on a large plotter but it could be done with A4 sheets

tiled together like the Darwin bed template.

The design is modelled in Openscad, down to the nut and bolt level, and is fully parametric so you can make any size machine and scale the rod diameters and motor sizes if necessary. The only limits are that eventually belts would need to be replaced by rack and pinion above a certain length. It also automatically generates a complete bill of materials for anything in the model.



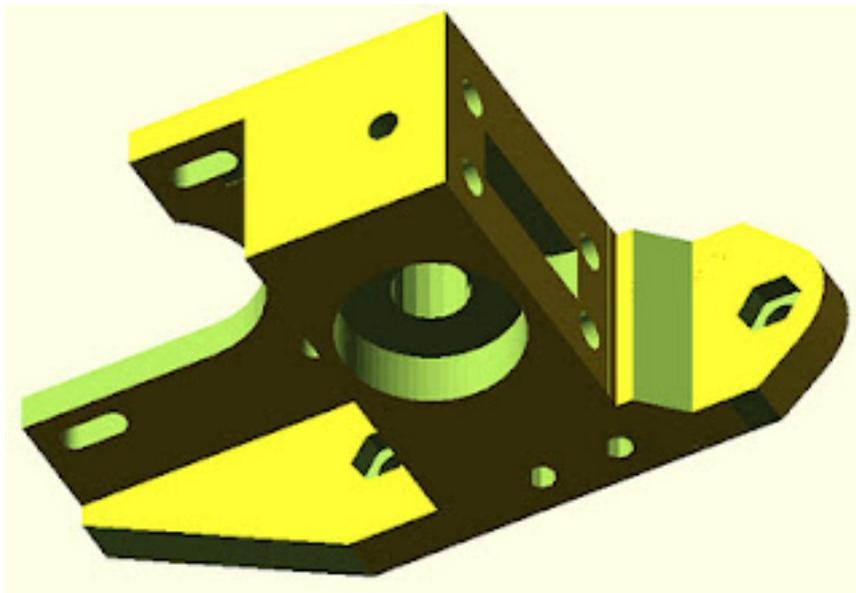
See also: [mendel90-extruder](#) and [mendel90-axes](#)

Merry Christmas!

# Mendel90 extruder

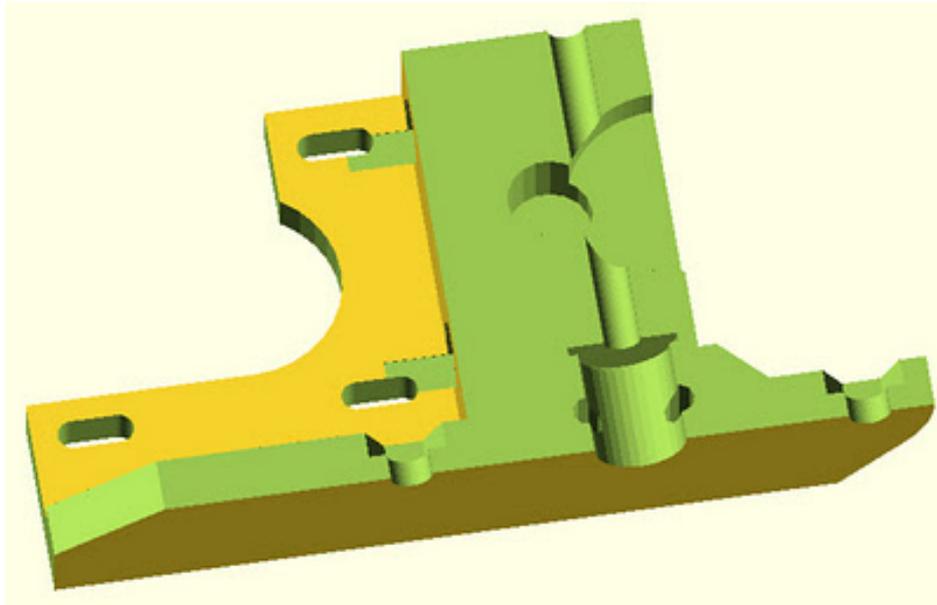
Thursday, 29th December 2011 by Nophead

The Mendel90 parametric design starts from the extruder dimensions and works outwards. I used a Wade's extruder for the Mendel sized version of the machine (I will need to sort out a smaller extruder for the Huxley sized version). My starting point was the Prusa version of Wade's. I tidied it up a bit aesthetically and made a few tweaks to the design and that had the side effect of making it easier for Skeinforge to slice correctly. The old version caused it to think layers were bridges erroneously. It now looks like this: -



The functional things I tweaked were: -

- I added nut traps for captive hex head bolts. That allows me to fasten it under the carriage with a couple of wing nuts, so I can swap extruders very easily.
- I brought the front of the bearing holder forwards 2mm. That stops the idler closing fully, which makes it easier to feed in new filament and allows the hobbed bolt to be removed without having to remove the idler. The downside is it would be less tolerant of smaller diameter hobbed bolts.
- I made the idler bolt holes slightly further apart so that I could make them larger without intruding into the bearing holders.
- I added a slot around the top of the hole for the insulator. When it was simply a blind hole it had radiused corners at the end due to the fact that the filament has a minimum bend radius. That meant that, unless the insulator was chamfered, it did not go all the way to the end of the hole.



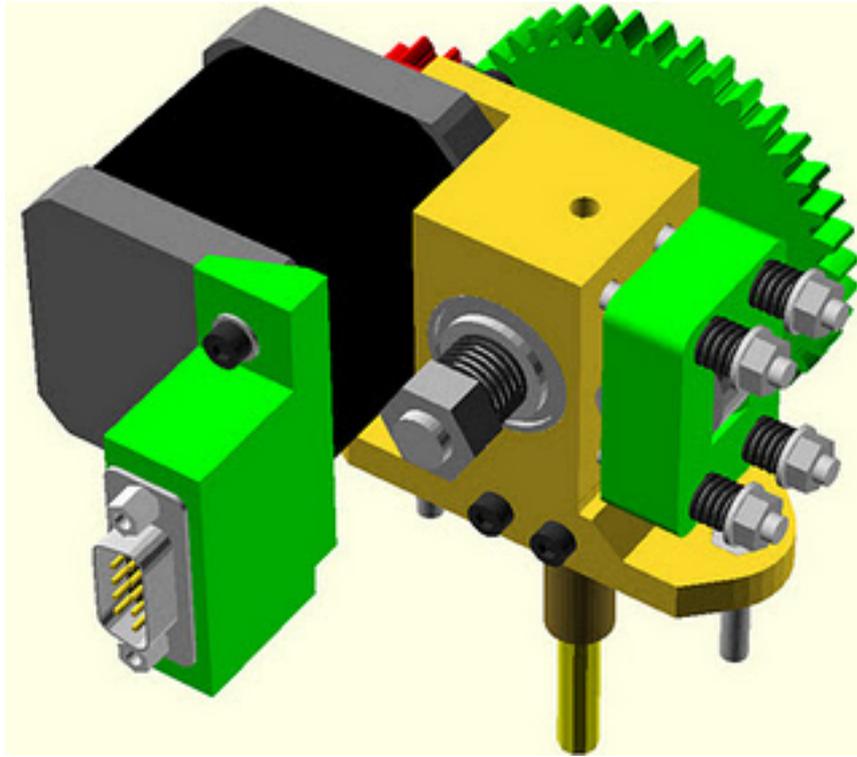
I use hobbed bolts and 10mm hot ends from [reprap-fab.org](http://reprap-fab.org). Wolfgang makes the bolts so that the big gear can be spaced off from the bearing with 5 washers. That allows the small gear to be placed the right way round, allowing the big gear to be removed easily. M8 washers can vary in thickness so I made a printed spacer 7.5mm long to replace them.

I don't use Greg's accessible version of the extruder because I never remove the idler. Once I have got the spring tension correct I don't like to change it. If I need to clean the hobbed bolt I simply reverse out the filament, remove the nut and then remove the big gear and hobbed bolt. It only needs cleaning if there has been a malfunction due to a filament tangle or a nozzle blockage.

To make the nut easy to remove, rather than use lock nuts or a Nyloc, I use a single nut and a weak spring. The spring stops the nut vibrating loose and gives enough pressure to keep the bolt in the correct position but it can be removed without using a spanner.

The extruder is the only part of the machine that wears out, so I have made it easy to swap out by adding a 9 way D type connector. D connectors screw together and have good strain relief for the cable, so they are reliable when subjected to constant movement. They are also rated for 5A per pin and 125°C, which is a good margin for this application.

I attach the connector with a bracket that is screwed to the motor by removing two of the motor's screws and replacing them with screws that are 5mm longer.



I have several extruders with difference nozzle sizes that I can change very quickly.

# Mendel90 axes

Friday, 30th December 2011 by Nophead

## Bearings

With the stainless steel bars that I use I found that PLA bushings only last a few hundred hours before they wear out. I tried Igus plastic bushings and they only lasted about the same length of time. I think you need ground rods rather than rolled to get a smooth enough surface for bushings. Possibly the lithium grease that I used was not suitable for plastic as I am sure other people must have got better life out of bushings.

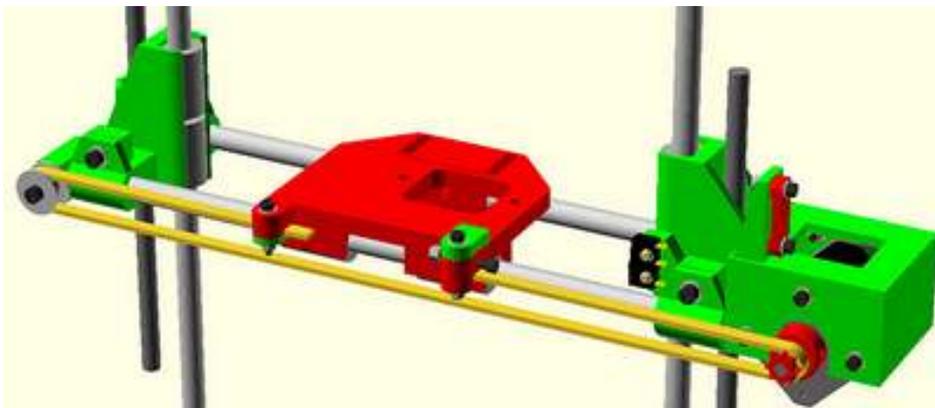
The ball bearings on my Mendel have proved very durable but they do wear flats on the rods after about a year of continuous use. This wouldn't be a problem except that the rods wear more in the middle, which leads to inconsistent Z height eventually. You can turn the rods to put the flats underneath and get many more years life.

I have run some LM10UU bearings for over a year non-stop and they have not worn the rods noticeably. I did have an LM8UU bearing suddenly decide it only wanted to go one way on my Prusa's X-axis. It just needed some oil to make it work again. I think the X-axis tends to dry out because it runs over the heated bed.

I made the Mendel90 prototype with 10mm rods because I had noticed the 8mm rods sag a little on my Mendel, that has a heavier bed and extruder though. 10mm rods cost quite a lot more than 8mm and the plastic parts get bigger so I intend to make an 8mm version and see how it compares.

## X-Axis

The X axis is similar to the Prusa but I have changed a few things: -



Note the axis is shortened in this picture, the belt has a twist not shown and a loop round the tensioning screw.

I lowered the idler and the motor to be in line with the bars because I noticed on my Prusa that the

belt tension tended to bow the bars upwards slightly at the ends. It does mean the belt is a bit closer to the heated bed but I haven't noticed any ill effects.

I swapped the positions of the Z bars and Z leadscrews so that the bearing holders face inwards. That means the belt tension tends to push the bearings into their holders rather than pulling them out. That allowed me to get rid of the cable ties.

There are clamps for the X-bars so they don't have to be exactly the right length. They can be adjusted a few mm lengthwise and then locked in place. The holes are open ended at the idler end to allow the bars to be removed without removing the Z-bars first.

The motor housing is a box shape to keep it rigid while still having only relatively thin walls. The hole in the top is for the wires and lets any heat out.

I didn't use a 608 skate bearing for the idler. They might be cheap and available world wide but I found they didn't work on my Prusa, whereas the 624 bearings used on the Sell's Mendel do work. Ball bearings have a chamfered edge, the bigger the bearing the bigger the chamfer and M8 washers are thicker than M4 washers. With 8mm bearings that leaves a gap big enough for the belt to ride down and bind, whereas with 4mm bearings the gap is much smaller so the belt simply brushes against the penny washer, rather than jamming.

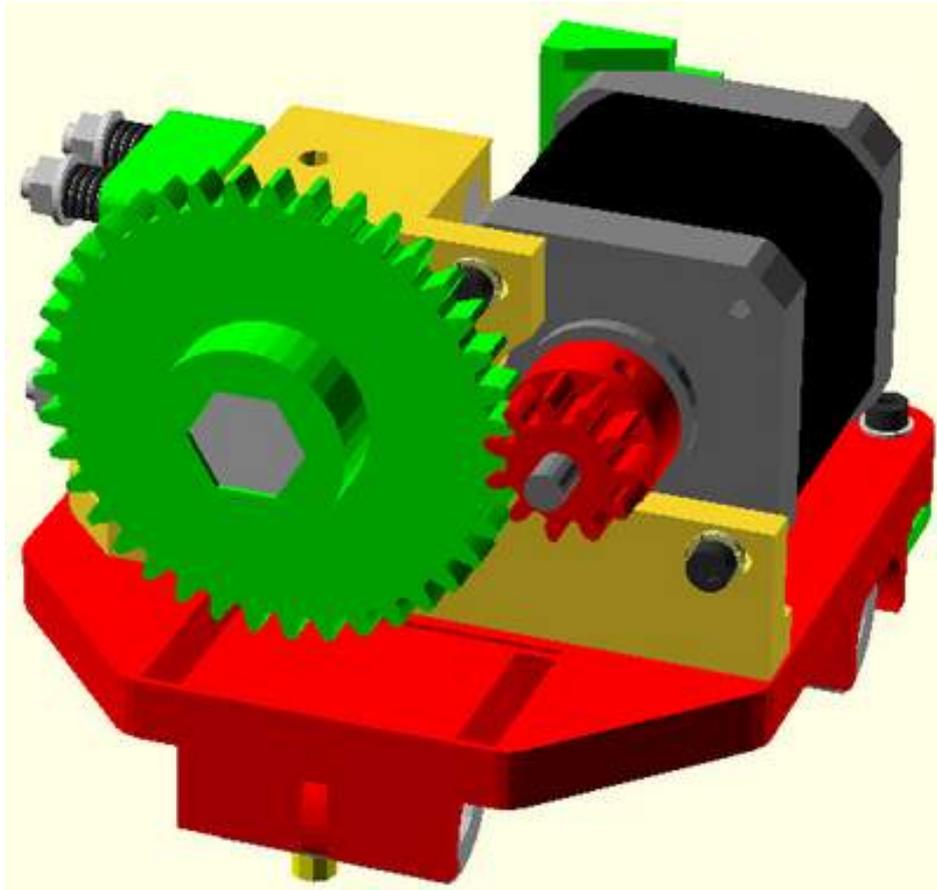
I prefer a bearing to a printed pulley with flanges or a crown pulley because if I am using a metal drive pulley for accuracy it does not make sense to have a printed idler.

I haven't added it to the model yet, but there is a half twist in the long return path of the belt so that the smooth side goes over the idler, not the teeth, to avoid any cogging. The twist in the belt doesn't seem to cause any problems, if it did I could revert to the technique here:

[hydraraptor.blogspot.com/2011/06/half-belt-hack](http://hydraraptor.blogspot.com/2011/06/half-belt-hack)

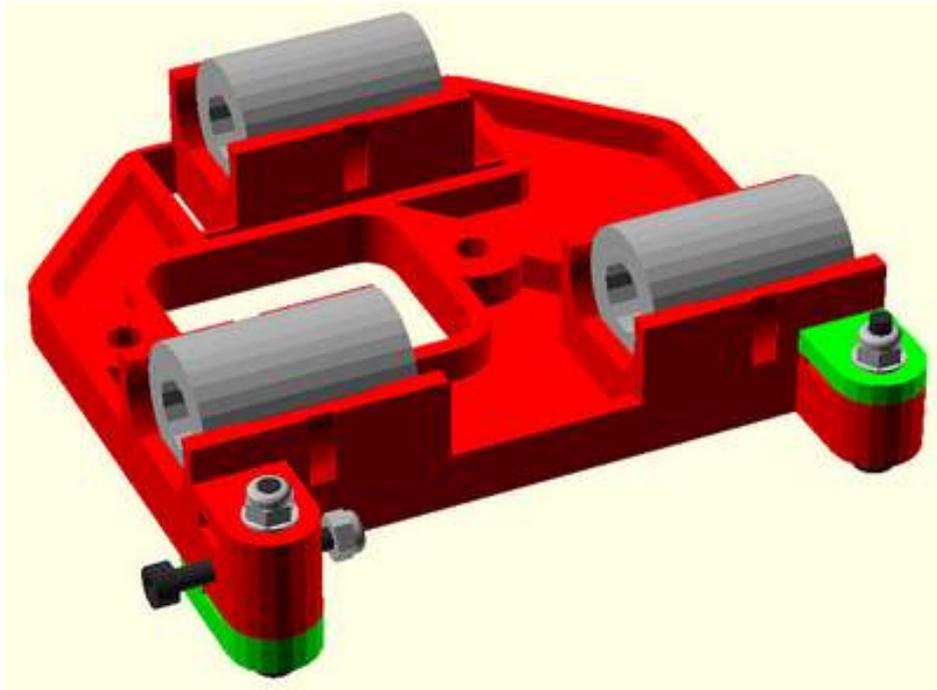
The belt tensioning is as Greg Frost's design: The ends of the belt are locked in place by clamps with mating teeth. A screw tightens a Nyloc nut against a loop of the belt.

The carriage is the full size of the extruder with the bearings optimally placed in a triangle and the belt attached at the ends. It does mean the carriage is a bit bigger than most but it makes best use of the space to achieve stability. I.e. the travel is limited by the extruder, so there is no point making the carriage smaller, other than reducing print time.



The carriage follows the rod on the two bearing side and only needs to be prevented from rotating around it by the third bearing. In order not to be over constrained the third bearing is suspended by thin but tall struts. That allows it to float horizontally but it is constrained vertically. This prevents binding in the event of the rods being slightly miss-aligned.

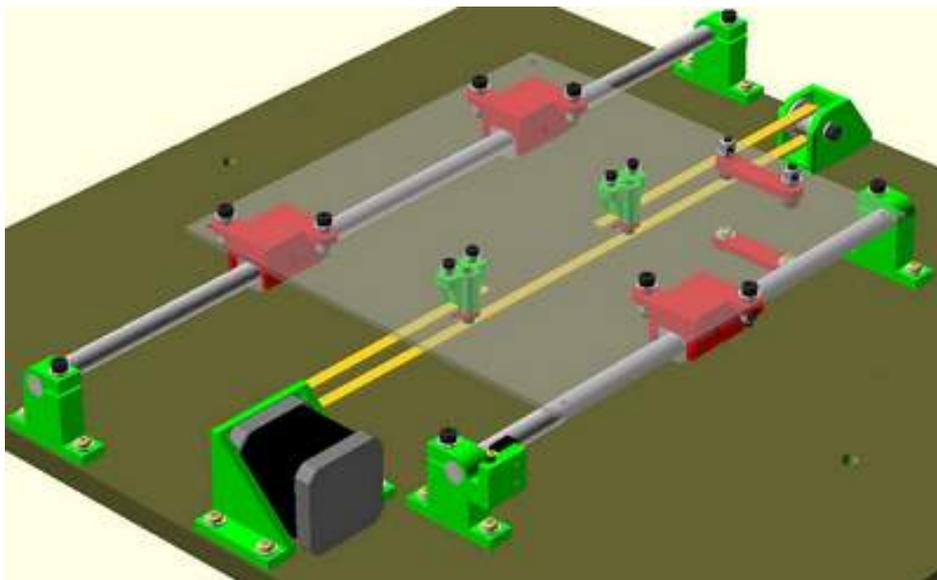
The underside of the carriage is shelled and ribbed to save print time but keep it rigid. That has been my philosophy on the design, strength through complexity of shape rather than chunkiness. Whereas other people have tried to reduce the printed parts to a minimum I have tried to put functionally first.



I found that I could not make bearing clamps in the horizontal direction with enough grip so I use cable ties as well on these. The bearings rest at each, end so a single tie in the middle is sufficient to keep them stable.

### Y-Axis

The Y axis sits on a flat sheet ensuring the bars lie in the same plane. Only three bearings are needed so the rod on one side can be shorter as it no longer needs to attach at the very front and back. The X-axis also uses three bearings and Z four, making the total ten, which is convenient as they tend to be sold in packs of ten. The belt is also shorter because the motor and idler can be brought inside the axis travel.



The Y motor bracket is a lot more rigid than the Prusa version due to its boxy shape and being screwed to the base instead of hung from bars. The bar clamps are also hollow boxes.

The bearing holders are the same as the ones on the carriage using tie wraps .

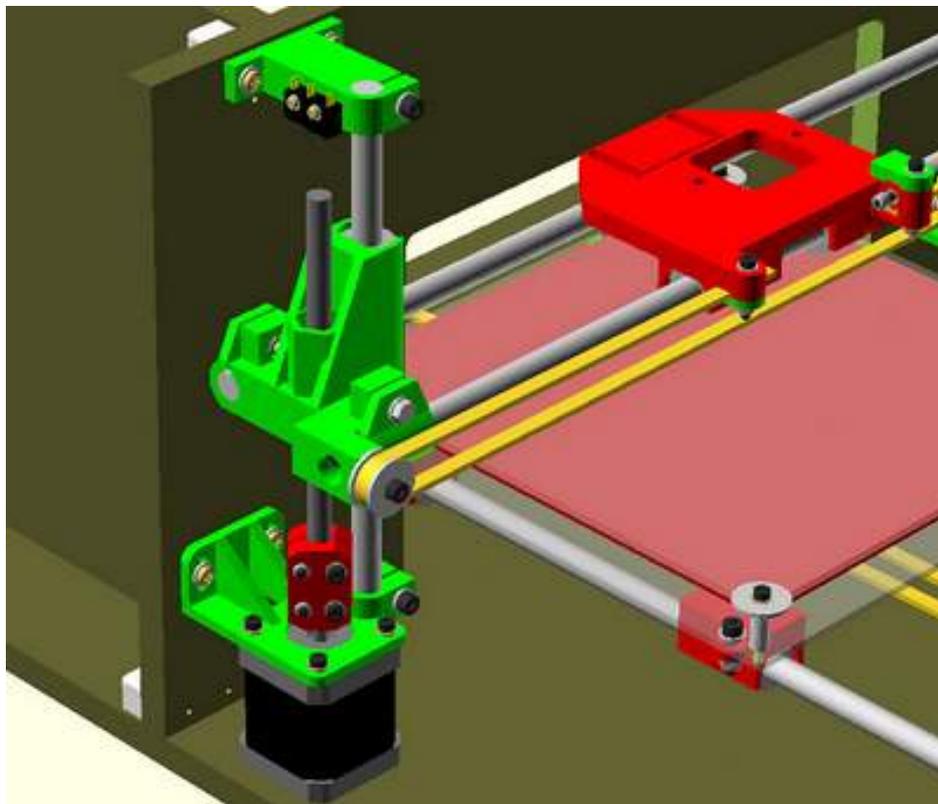
Alignment is easy, all the bar clamps and bearing clamps have slotted screw holes allowing a little side to side movement. Initially all the screws are left loose. The long bar is set at right angles to the gantry using a set square and then the bar clamp screws are tightened. The bearing clamps on that side are then tightened. The y-carriage can then be moved backwards and forwards to pull the second bar into alignment before those are tightened. On my todo list is to float the third bearing like I have done on the carriage.

Again the belt has a half twist in the lower return path, not shown on the model. Belt tensioning is easy because the idler has a slot to allow it to be adjusted. The single mounting hole also allows the angle to be adjusted to centre the belt. I plan to move it to the front and put the motor at the back as it makes the wiring shorter and the idler adjustment more accessible. I used two 624 bearings side by side to allow the belt to wander a bit without binding. I seemed to need that on Y but not X. I may move to two on the X-axis as well to give a completely frictionless arrangement.

If you are wondering what the two large holes in the base are, they are there so that dual shaft motors can be used.

### Z-Axis

I moved the motors to the bottom to eliminate the possibility of the couplers slipping off. I made the couplers as skinny as possible to get the bar close to the lead screw. That makes the X ends smaller and allows the Z bar to rest on top of the motor giving a metal connection from the base to the top limit switch minimising the effect of the wood shrinking and expanding. For normal Reprap software it probably needs an adjustable bottom limit switch instead.



Note the axis is shortened in this picture.

The Z bars are automatically parallel to the gantry because the distance at the top and the bottom is set by printed parts. The bar clamps at each end of the rods are identical allowing the axis to be made vertical with a set square. This is done at the left hand side and the other side is made parallel by moving the axis up and down before tightening the screws.

I kept the facility for anti-backlash nuts and springs but the only machine I needed to fit them on was my Prusa. I am not sure why, but even the weight of an extra motor was not enough to overcome the backlash with gravity. I think it must have either been due to binding or perhaps the grease I used was thick enough to need some force to squeeze it out of the way. I needed stiff springs and I had to turn up the z-motor current after fitting them. The advantage of not fitting them is it gives some protection against a head crash as the maximum force you can apply downwards is the weight of the X-axis and extruder.

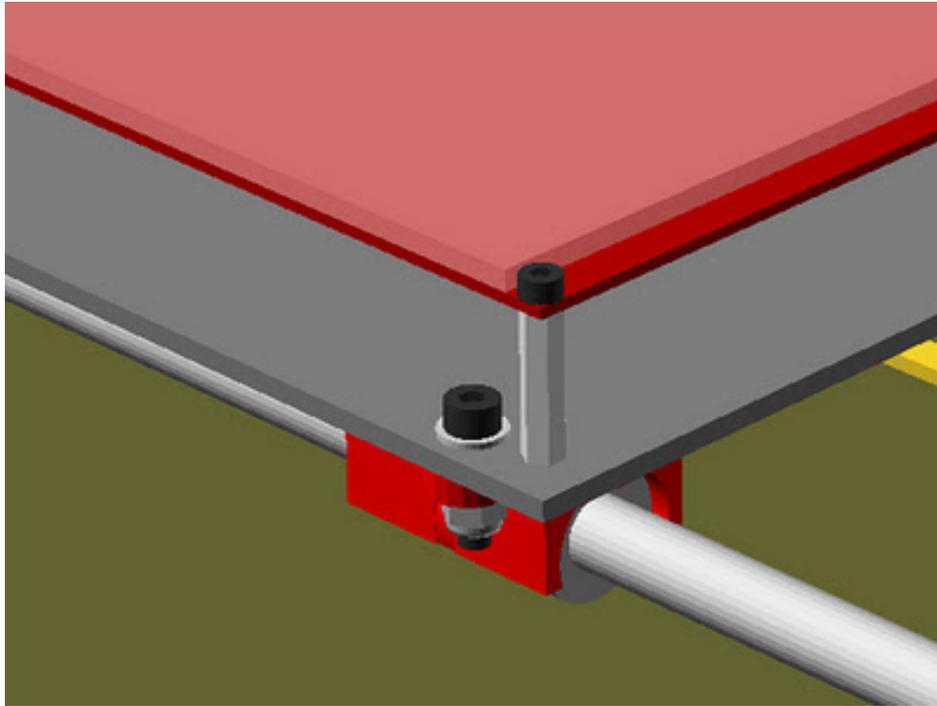
I considered using a single motor and linking the screws with bevel gears and a drive shaft. That would be cheaper than a second motor or a belt but I stuck with two motors for simplicity at the moment.

## **Bed**

I have previously used 6mm aluminium tooling plate with aluminium clad power resistors for my heated beds. These work well but they are heavy. The Prusa PCB heater with a 2mm glass sheet on the top makes a much lighter solution. The picture above shows it clamped down with penny washers but bulldog paper clips work better.

I use 3mm Dibond for the Y-carriage because it is light, stiff and stable. I tried 6mm MDF on my Prusa but it warped due to the heat and the bed never stayed level for long. I don't know how other people manage to use it.

The best bed mounting solution I have tried so far is 20mm brass hex pillars. I tap the carriage holes M3 and screw the pillars into it. I can then level the bed by adjusting them and use the screw in the top to lock the position. I don't like to use springs because they let the bed wobble.



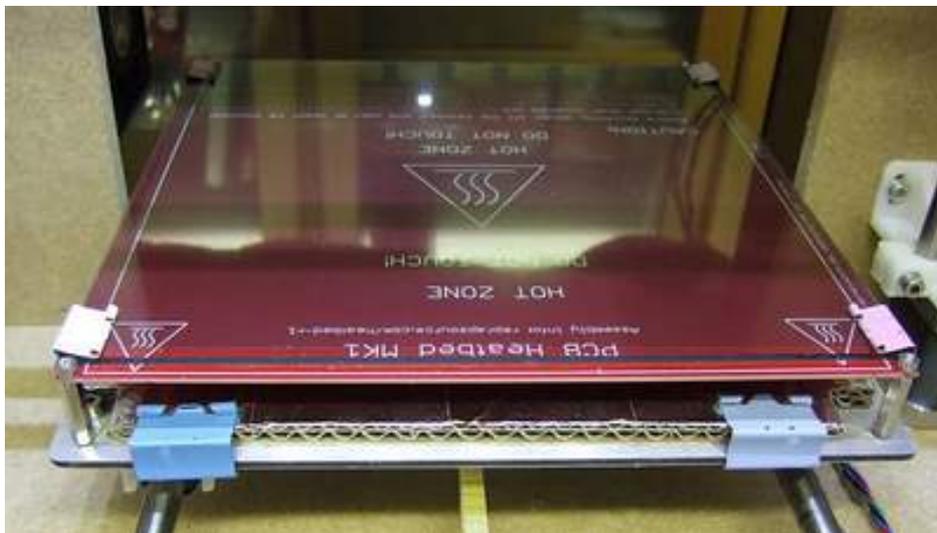
To level the bed I put M3 washers under the back two pillars and screw them tight and lock them. I then twist the Z motors by hand to make both sides level at the back relative to the nozzle. I then adjust the front two pillars to get the bed level front to back.

The process is easy but tedious because all the adjustments interact to some extent, so you have to keep going round them. It would be better if the bed had a single mounting hole at the front in the middle, as you only need one adjustment to get the bed level from front to back. I need to make a smaller version of my Z-probe so I can auto level the bed.

I like to use an air gap under the bed for insulation so that I can cool it rapidly with a fan at the end of the build to make the parts release easier. The air gap provides enough insulation but the Dibond below still gets to around 50°C. I added a heat shield made from corrugated cardboard covered in aluminium foil tape and the Dibond no longer gets warm at all.



The slots are to clear the screw heads. I stuck it down with double sided tape but that did not hold so I added bulldog clips. If I was making another I would bolt it down.



I haven't made any measurements yet but I think the difference in temperature between the middle and the edges is bigger than my aluminium beds. I intend to try adding printed baffles at the front and the back to stop the movement of the bed pushing cold air under it.

I think I can improve the temperature distribution by changing the PCB pattern. The problem at the moment is that if the middle runs a bit hotter then the tracks local to it will have a higher resistance than those at the edges, which are connected in series with it. That means the middle will get more voltage and become even hotter relative to the edges, positive feedback. A better

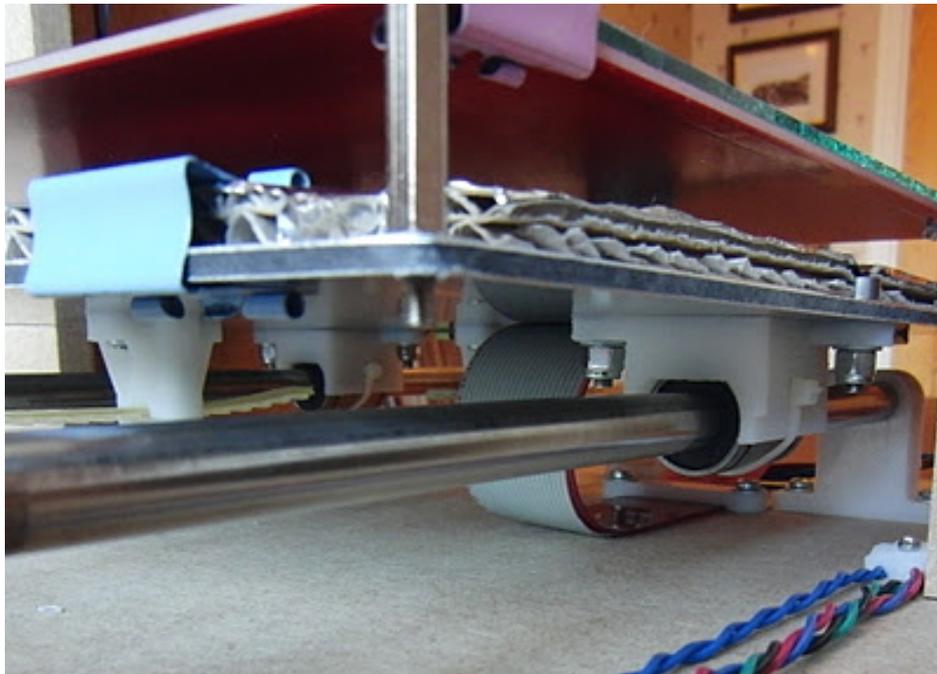
arrangement would be to have concentric rings of tracks running through areas that are likely to be the same temperature, wired in parallel. That way if the middle got hotter it would only have tracks near the middle in its circuit, so the increase in resistance would lower the current and give some negative feedback.

Another thing I would change would be to remove the silk screen from the top layer as it has some thickness that will reduce the thermal contact with the glass.

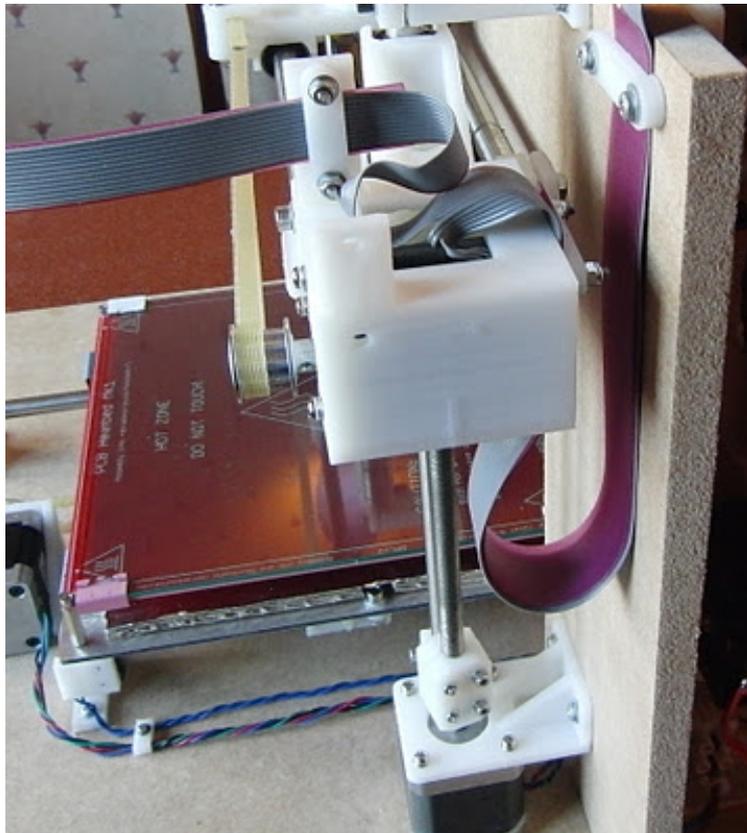
### Cables

Larger CNC machines use cable chains to enforce a minimum bend radius on moving cables to stop them breaking. There have been several printable versions on Thingiverse but I feel they would give more friction than desirable for a small machine like this. Ribbon cables are very flexible in one direction and are surprisingly rated for 300V, 1.4A and 105°C.

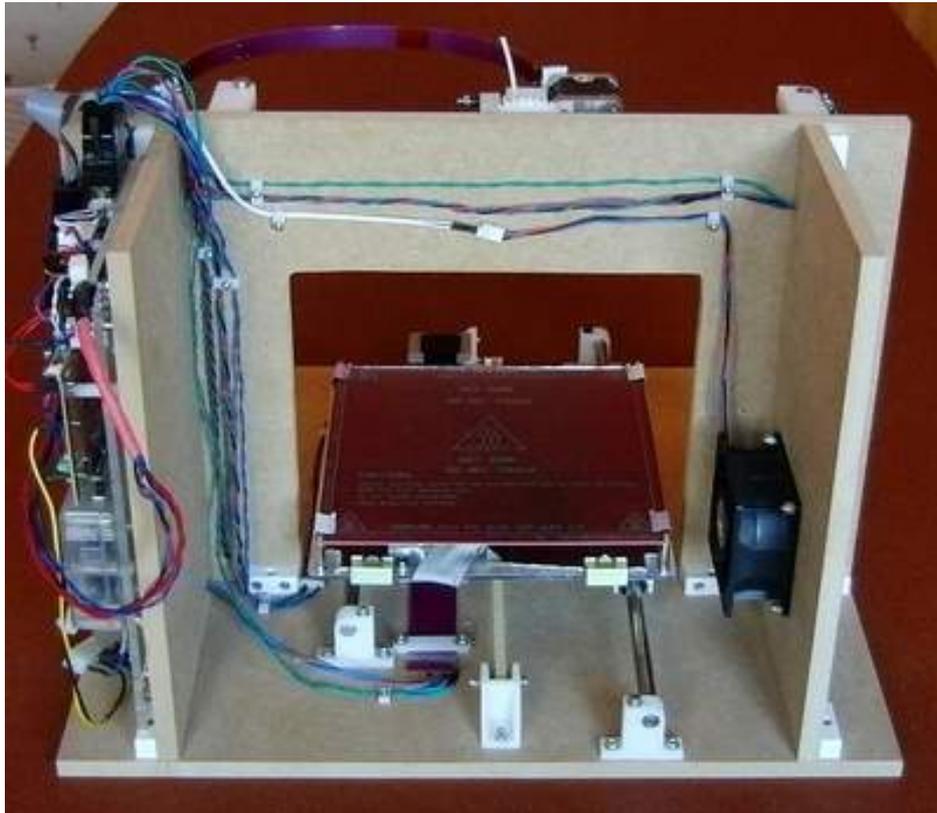
For the heated bed I use ten wires in each direction plus 2 for the thermistor. I clamp it at both ends with a thin strip of polypropylene about 0.5mm thick. That forms the equivalent of a miniature cable chain but with very low friction. Here is the one under the bed: -



This one feeds the X motor and the extruder: -



The rest of the wiring is done on the back of the gantry with printed cable clips : -



The fan on the left is a powerful 80 CFM fan that I use to cool the bed from 110°C to 30°C in about 6 minutes.

The only down side of ribbon cable is that you get some inductive cross talk from the motor signals

to the endstops. That doesn't affect my firmware as I only read the endstops during homing and a simple retry loop sorts that out. For firmwares that constantly monitor the endstops a simple RC filter on the inputs should fix it.

This version of the machine I call the Sturdy model. It uses 10mm rods, M4 fasteners and has a build area slightly bigger than a Mendel: 214 x 214 x 150mm. The next version I try will use 8mm rods, M3 fasteners and have an acrylic frame. I will reduce the build area to 200 x 200 x 140mm, same as Mendel so it will be more of an equivalent. I will also make a Huxley equivalent with NEMA14 motors and 6mm rods. The Mendel sized variant will cost a bit less but I doubt the Huxley will be any cheaper.

# Bearings, Bushings and Bars

Saturday, 7th January 2012 by Nophead

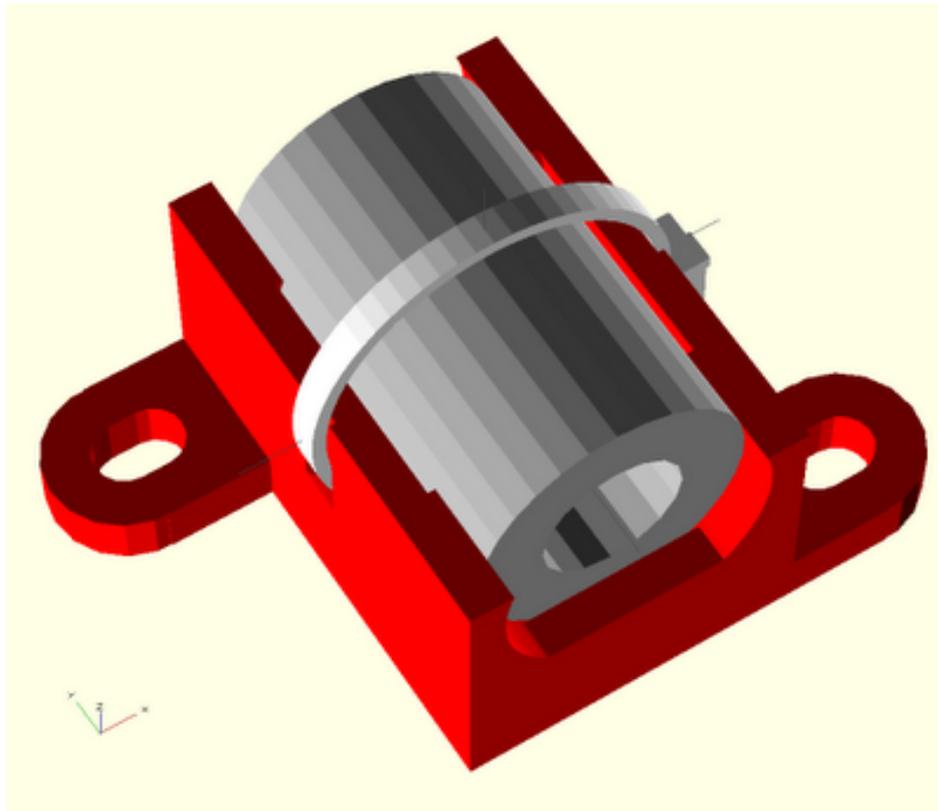
My last post started a discussion about why I got only a few hundred hours of use from PLA bushings and in particular commercial IGUS bushings. I think I mounted the IGUS bushings well enough. I printed PLA holders and reamed them to a 10mm bore, which gave a nice press fit.



I had intended to use a small self tapping screw to retain the flange but found I didn't need them. That is what the two holes are for. They are triangular because they are polyholes.

The holders have slotted screw holes and were screwed to the underside of my Prusa's Dibond Y carriage. I started with them loose and then tightened the screws as I ran the axis up and down to ensure they were aligned well. I then applied lithium grease.

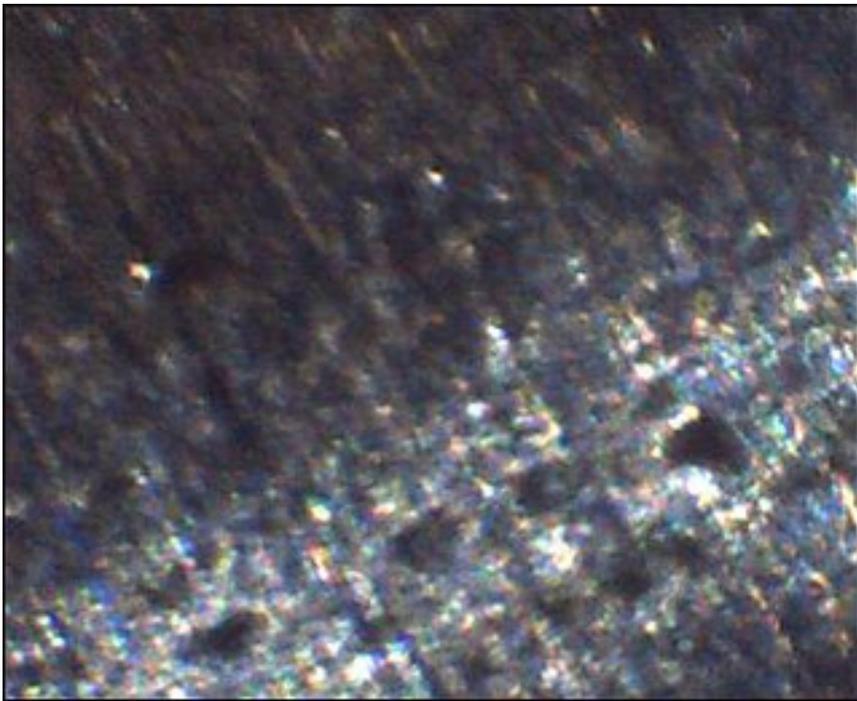
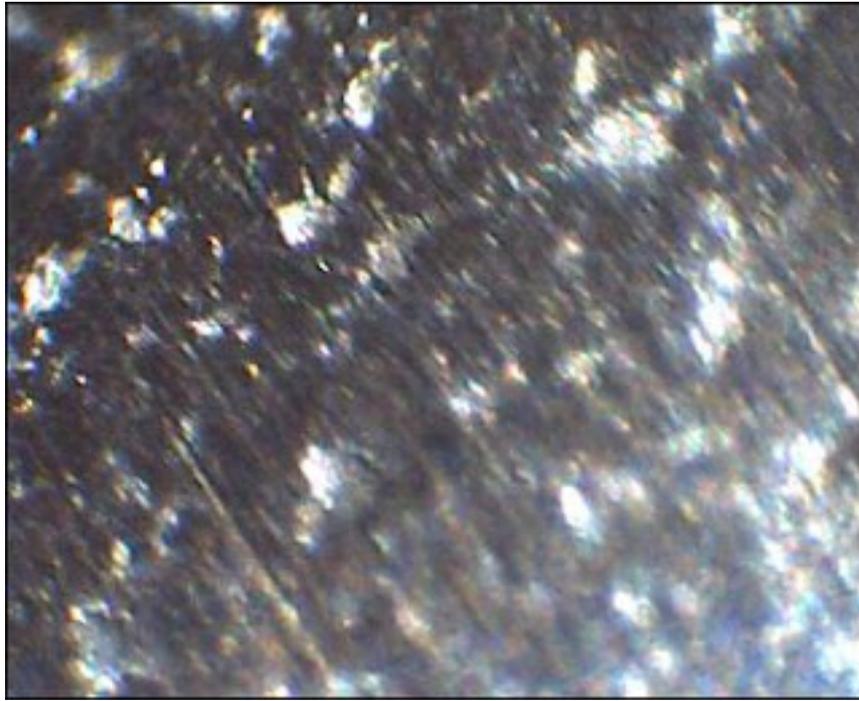
When first fitted they had no slop and very low friction. After a few days of continuous use the holes in the bushings had elongated and there was noticeable slop. At that point I replaced them with LM8UU bearings in prototype bearing holders I designed for the Mendel90.



These have run for thousands of hours with no noticeable wear. They do have more friction than bushings though. It seems higher to start with but they seem to "wear in" quite quickly and it drops.

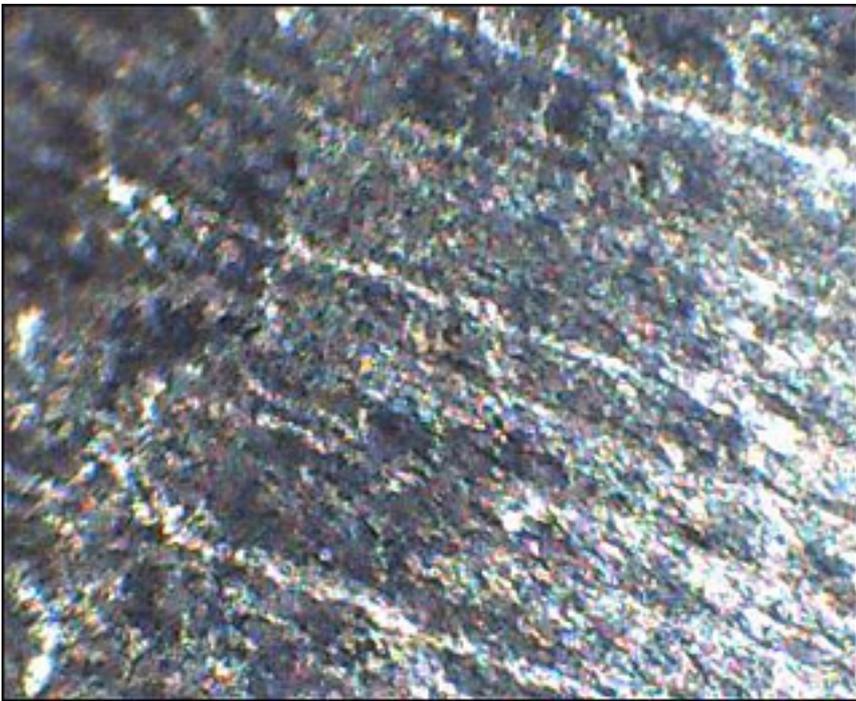
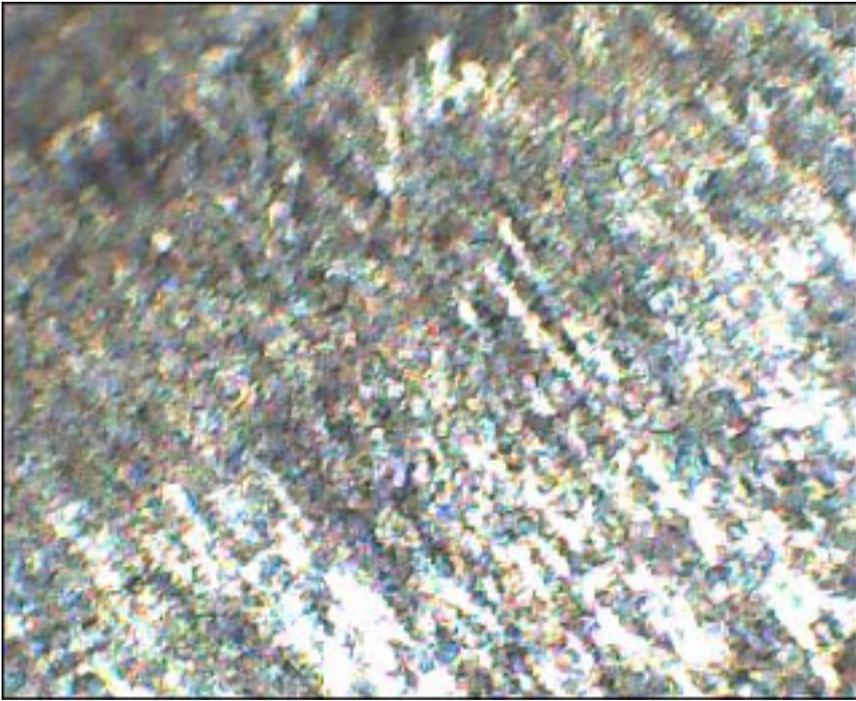
My suspicion was that the surface quality of the stainless steel rods that I used was to blame, so I have just had a look with a microscope. I used a cheap USB "Traveller" microscope from Aldi and a times 4 objective lens. The magnification is much greater than that though when photographed and blown up to screen size.

Here are a couple of pictures of an off-cut from the stainless steel rods I used on my Mendel: -



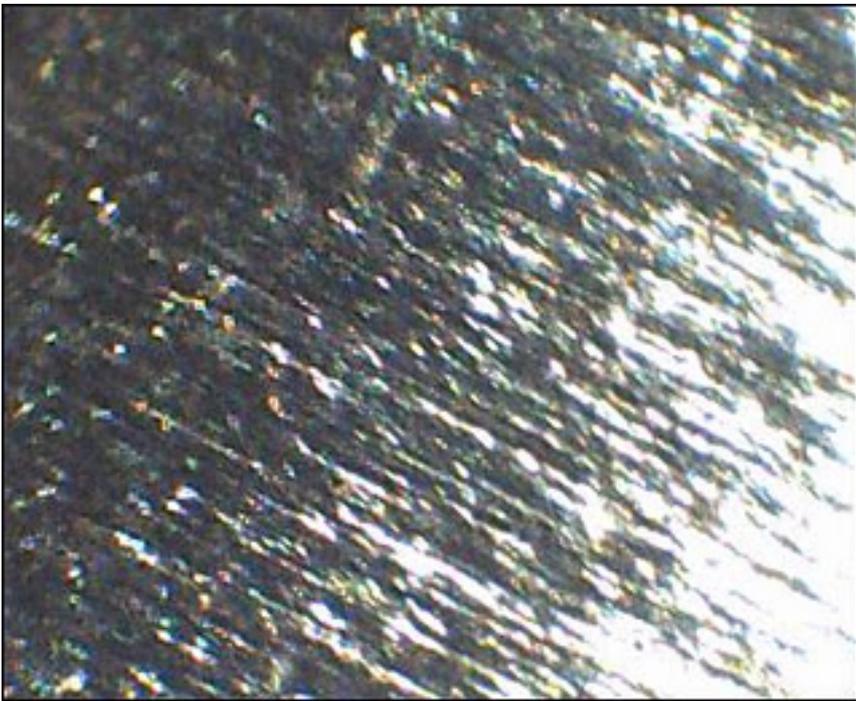
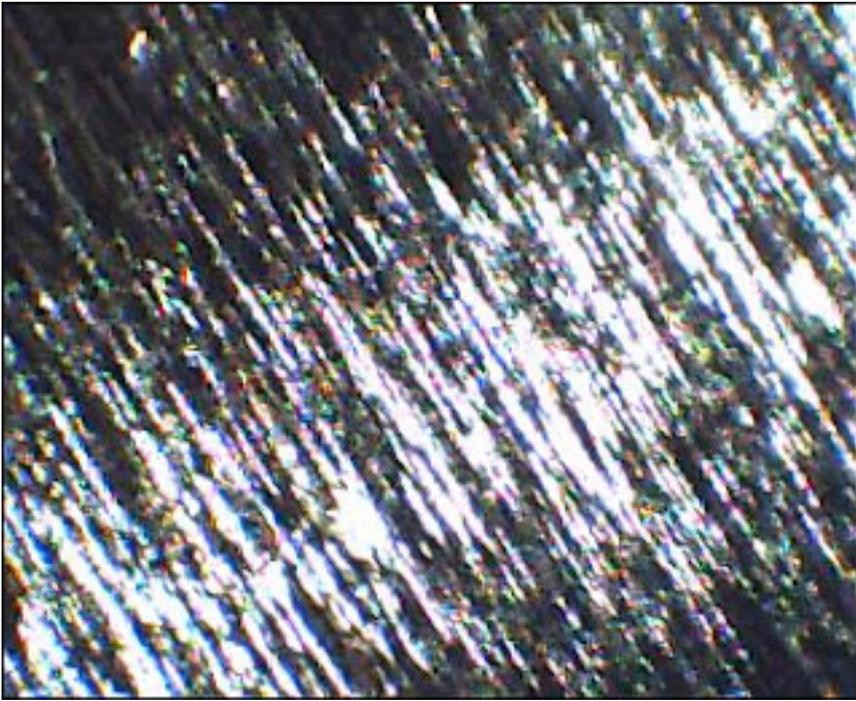
Obviously you can only have a small strip in focus due to the curvature of the rod but you can see it looks far from smooth. The difference between the pictures is mainly the lighting angle.

Here is a mild steel rod bought on eBay, sold for Reprap use, so probably typical of what most people use: -



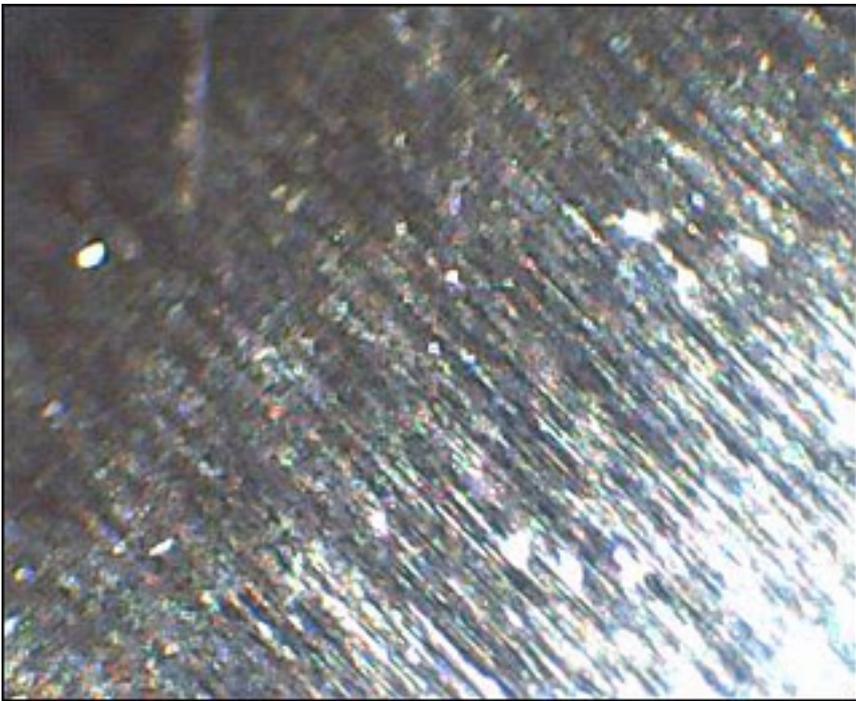
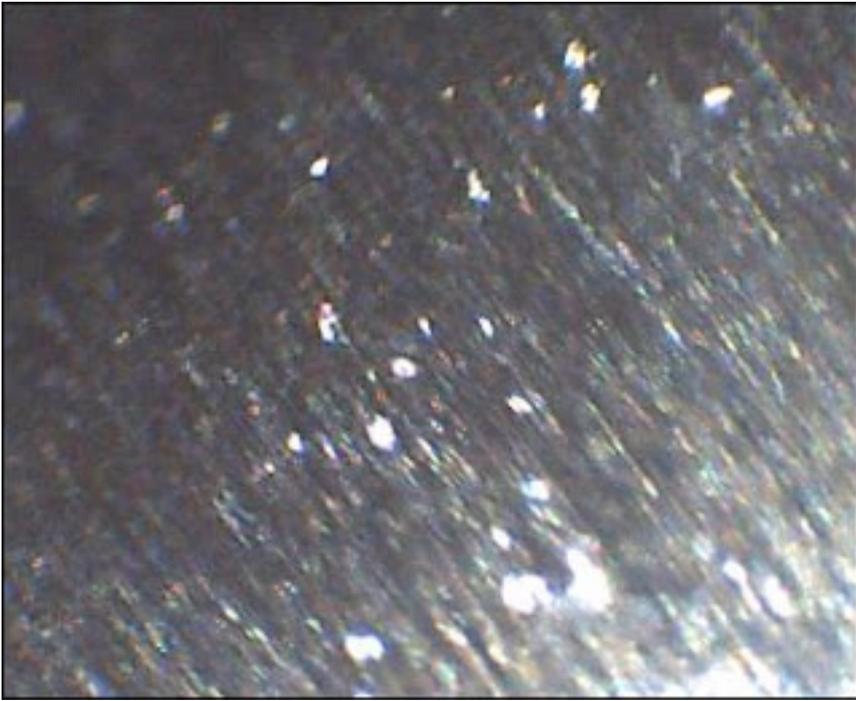
Quite a lot smoother, so hopefully most people get better life from PLA bushings than I did.

Here is a bright steel rod from a 2D printer, or maybe a flat bed scanner, I can't remember which, but it will have used bushings: -



It seems to have a finer grain structure but doesn't look particularly smooth.

And here is a "precision round rail (Induction Hardened)" sold for use with linear bearings that I got from Zapp Automation.



It looks the best out the four, so I guess you get what you pay for.

I think for soft bushings to last you need high quality rods. LMUU bearings seem to be more tolerant.