Paper:

Development of the Master Hand for Grasping Information Capturing

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Analysis of human hand grasping operation provides information for developing robot hand grasping algorithms based on human knowledge and experience. Hand grasping analysis involves finger movement and contact force acting on the fingertips. We present a master hand put on a human hand to measure fingertip movement and contact force acting on the human fingertips. The master hand consists of serial links, six-axis force/torque sensors installed on the fingertips, a base, a glove, and an inclination sensor. We developed the master hand to clarify human grasping strategy. We collect data by having a subject act under the physical constraints as those of the robot hand. Obtained information is used to develop grasping algorithms for robot hands. Starting with a discussion of the concept behind master hand development, we detail the mechanism of the master hand and demonstrate its features.

Keywords: robot hand, master hand, grasping information, six-axis force/torque sensor

1. Introduction

Human grasping involves an exquisite combination of finger movement and contact force which exerted by fingertips on an object. Robot-hand control algorithms should take advantage of human knowledge and experience by measuring and analyzing data on human hand grasping. In measuring human hand grasping, fingertip movement should be measured rather than joint movement, because we manipulate an object mainly using the fingertips. And we grasps an object while controlling grasping force for maintaining dynamic balance and stability in grasping, the analysis of human hand requires data on both finger movement and grasping force.

Until now, a device for measuring finger movement has been developed [1–3]. Yamaguchi et al. analyzed finger movement using a parallel-link goniometer [1]. Rohling et al. developed the Utah Dextrous Hand Master, which has exoskeleton finger consists of three pairs of parallel link [3]. CyberGlove (Virtual Technologies Inc. made) is commercially available for a computer graphics interface with a bending sensor on the back of the finger of a glove. Each of these devices measures human finger joint movement. To obtain fingertip movement required to analyze grasping operation, calibration is required to account for individual differences in finger size [4]. On the other hand, a device for measuring finger pressure distribution has been developed. Shimizu et al. developed a sensor glove having distributed tactile sensors to investigate pressure distribution in grasping [5]. The data measured by this device is only pressure distribution, friction force and moment acting on the finger surface important for stable grasp are not measured. No device has been developed, to our knowledge, that simultaneously measures finger movement and contact force acting on the fingertip.

To analyze grasping operation, we developed a master hand that simultaneously measures fingertip movement and contact forces acting on the fingertip. We begin by detailing the development concept and mechanism, then introduce data sampling and device features.

2. Development of Master Hand

2.1. Development Concept

Grasping operation can be defined as dynamically changing contact between the finger and object to make the object into an intended state. We conduct skillful manipulation while dexterously moving the fingers to dynamically control contact between the fingers and object using our knowledge and experience. Skillful manipulation with robot-hand should be realized by measuring contact data between the finger and object, and reproducing the contact status. Therefore, our proposed master hand measures contact data, i.e., fingertip movement and force which the fingertips exert on an object.

Grasping involves physical contact between the finger and object, and is affected by the finger shape and material. Human and robot fingers differ in shape and material, so human hand grasping data may not be used as is for robot hand control. On the contrary, grasping data under similar physical constraints to robots may be useful for

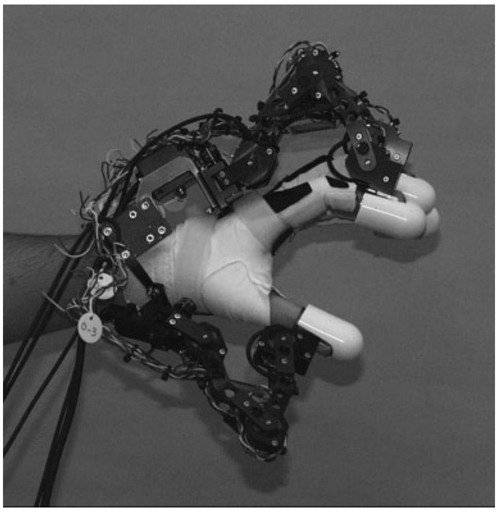


Fig. 1. Photograph of the master hand for grasping information capturing.

controlling robot hands. Our proposed master hand was developed for measuring human grasping subjected to the same physical constraints as to determine grasping operations and to use data for designing robot hands, teaching, and developing grasping algorithms.

The master hand had the following development specifications:

- Make object operations by fingertip-grasping to be objective tasks.
- Measure fingertip movement instead of that of the finger joint.
- Measure fingertip movement throughout the full joint range.
- Fingers measured are the thumb, index finger, middle finger, and ring finger.
- Fingertips of the master hand have the same shape and material as the robot hand [6] we are currently using.
- Use the same sensors (six-axis force/torque sensors) [7] at the fingertip installed on the robot hand.
- To investigate the effect of fingertip shape and material on grasping, make the fingertip easily replaced.
- Make fingertip movement and force data describable with respect to a hand frame on the back of the master hand.

2.2. Configuration of Master Hand

Figure 1 shows a photograph of our master hand. **Fig. 2** shows a design drawing with the glove being omitted. The master hand is for left hand and consists of serial links (1) for measuring fingertip movement, six-axis force/torque sensor (2) placed on a subject's fingertips, base (3), gloves, and inclination sensor (4). The fingertip of the glove is cutoff and the base sewn on the back of the glove. The base holds the inclination sensor to measure the orientation of the back of the hand. With the serial link measuring fingertip movement, a potentiometer (5) is located at each joint of the link and connected to the base and the force/torque sensor at fingertip. The orientations of each fingertip and gravity compensation of the force/torque sensors are calculated by using the inclination sensor data and potentiometer data of the serial link. The master hand is placed on a subject's by putting on the glove and inserting the fingertips into the finger stall of the force/torque sensors.

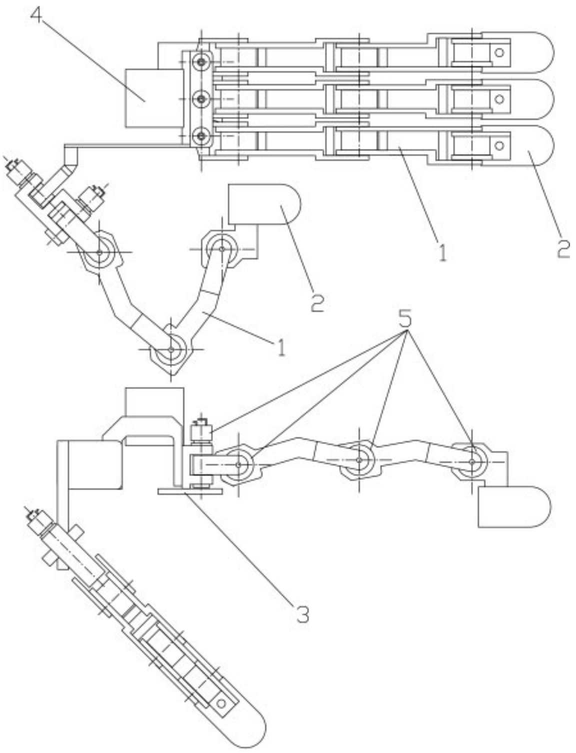
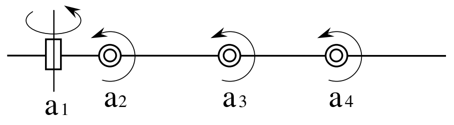


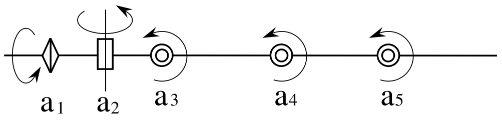
Fig. 2. Configuration of the master hand.

2.3. Measurement of Fingertip Movement

The master hand measures fingertip movement of thumb, index finger, middle finger, and ring finger. The degree of freedom (DOF) of the serial link is designed based on the degree of freedom of fingers to measure fingertip movement created by finger joints as precisely as possible. The finger joints considered here are the metacarpophalangeal (MP) joint, proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint, in the sequence from nearest the palm [8]. A simplified human finger model has four DOF in total, two DOF of adduction/abduction, and flexion/extension for the MP joint, one DOF of flexion/extension for the PIP and DIP joints, respectively [9]. Based on the simplified DOF finger model, we arranged a potentiometer for detecting



(a) Finger



(b) Thumb

Fig. 3. Kinematics of the master hand.

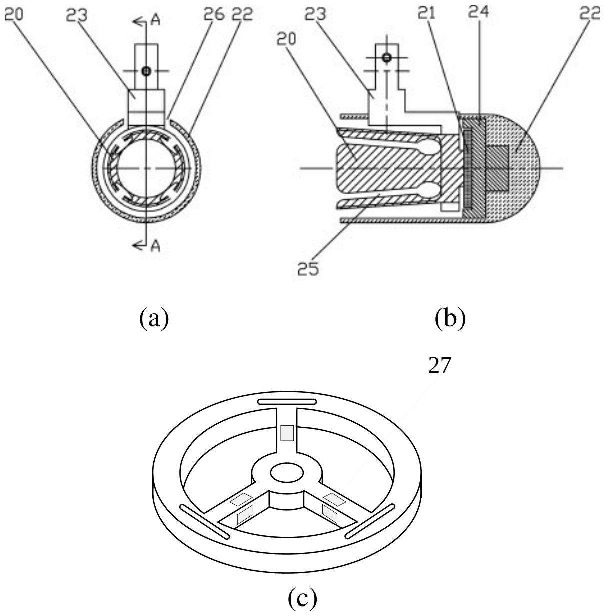
Table 1. Joint angle range of the master hand.

(a) Finger

a_1 [°]	a_2 [°]	a_3 [°]	a_4 [°]
−20 - 20	−60 - 75	−140 - −50	−75 - 75

(b) Thumb

a_1 [°]	a_2 [°]	a_3 [°]	a_4 [°]	a_5 [°]
−90 - 90	−10 - 45	−25 - 120	−140 - −50	−75 - 75



(a) (b)

(c)

Fig. 4. Configuration of the six-axis force/torque sensor which can be mounted on a human fingertip.

adduction/abduction near the MP joint, and potentiometers for detecting flexion/extension near the MP joint, DIP joint and in the serial link between MP joint and DIP joint, respectively (**Fig. 2**). The potentiometer for detecting adduction/abduction of the MP joint is arranged so that the rotation axis is perpendicular to palm and three potentiometers for detecting flexion/extension are arranged so that the rotation axes are perpendicular to the link segments and rotation axis of adduction/abduction. **Fig. 3(a)** shows the arrangement of the joint of the serial link for fingers. **Table 1(a)** shows a joint range of finger movement. Here, a_1, a_2, a_3 and a_4, represent joint angles of MP adduction/abduction joint, MP flexion/extension joint, PIP joint and DIP joint, respectively. **Fig. 2** shows the joint angle 0° at each joint.

Thumb joints are carpometacarpal (CM) joint, metacarpophalangeal (MP) joint, and interphalangeal (IP) joint, in the sequence from nearest palm [8]. A simplified thumb model has five DOF in total, three DOF of flexion/extension, adduction/abduction and opposition for the CM joint, and one DOF of flexion/extension for the MP joint and IP joint, respectively [9]. As shown in **Fig. 2**, three potentiometers are arranged near the CM joint for detecting flexion/extension, adduction/abduction and opposition. Rotation axes of these three potentiometers are perpendicular in turn. And two potentiometers for detecting flexion/extension are arranged near the IP joint and in the serial link between the CM and IP joint. Rotation axes of these potentiometers are perpendicular to the link segments of the thumb. **Fig. 3(b)** shows the arrangement of the joint of the serial link for the thumb. **Table 1(b)** shows joint range of thumb movement. Here, a_1, a_2, a_3, a_4 and a_5, represent joint angles of the CM opposition joint, CM adduction/abduction joint, CM flexion/extension joint, MP joint and IP joint, respectively. Here, **Fig. 2** shows the angles of the CM opposition joint and CM adduction/abduction joint are 0°. **Fig. 3** shows joint angles of CM flexion/extension joint, MP joint, and IP joint are 0°. The thumb link is attached to the base with a roll angle of 30° and a pitch angle of 54°.

2.4. Finger Installation Six-Axis Force/Torque Sensor

Figure 4 shows the configuration of the finger-installation six-axis force/torque sensor. **Fig. 4(b)** is a cross section of **Fig. 4(a)** A-A. The finger-installation six-axis force/torque sensor consists of finger stall (20) for inserting a human finger, an elastic component (21) for transforming force into output signals of strain gauges, and a finger cap (22) having the same material and shape as the fingertip of the robot hand [6]. The elastic component of the six-axis force/torque sensor is the same as the NANO sensor [7], having a structure in which a peripheral ring and central member are connected by three beams. Each beam holds strain gauges (27). For the six-axis force/torque sensor, a link combination part (23) is provided to be connected with the serial link by a screw clamp, so the fingertip is easily taken off. The link combination part (23) is coupled with the base of finger stall (20). The rated load and resolution of the force/torque sensor are shown in **Table 2**. The sensor amplifier has a low-pass filter built in, whose cutoff frequency is 100 Hz.

3. Robot Hand System

Figure 5 shows the entire robot hand system. The system consists of the master hand for measuring human

Table 2. Rated load and resolution of the sensor.

Rated Load	f_x, f_y, f_z	[N]	11.8
	m_x, m_y, m_z	[N·m]	0.1
Resolution	f_x, f_y	[N]	7.8×10^{-3}
	f_z	[N]	2.5×10^{-2}
	m_x, m_y	[N·m]	4.9×10^{-5}
	m_z	[N·m]	6.9×10^{-5}

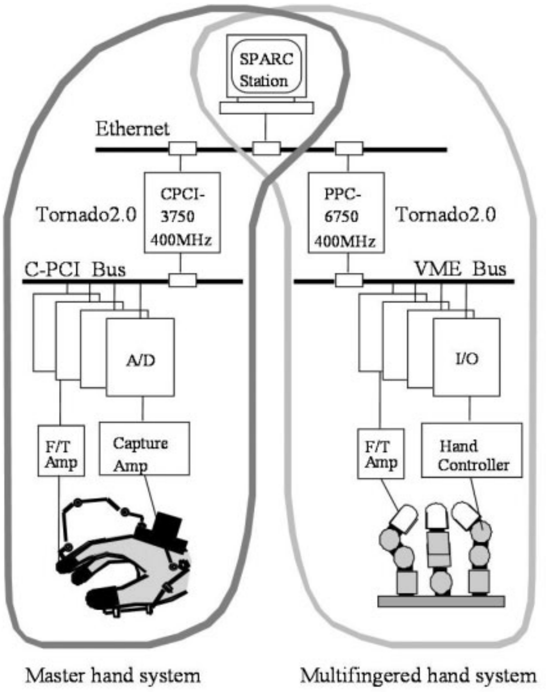
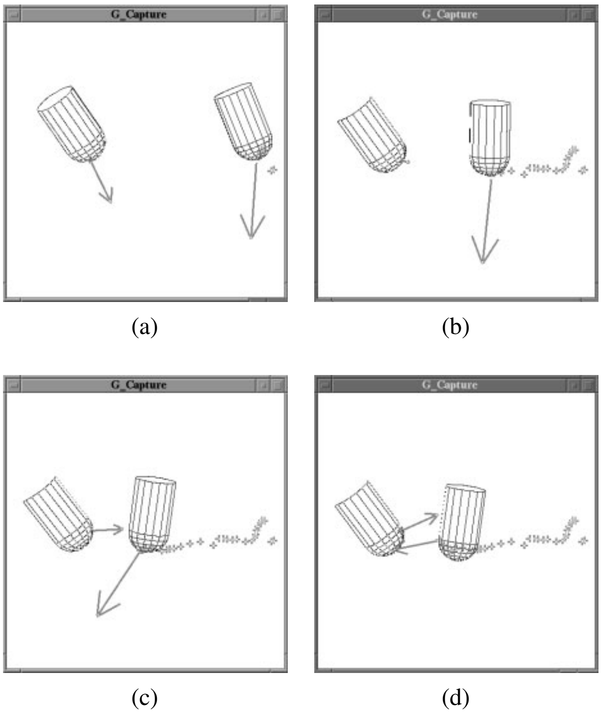


Fig. 5. Overall view of the hand system.

grasp and multifingered robot hand, each system consisting of an upper non real-time layer and lower real-time layer.

The real-time layer of the master hand is implemented in a PowerPC on the CPCI-Bus and the task is executed under a real-time OS Tornado 2.0. The real-time layer captures joint angle data, inclination sensor data, and force/torque data of each finger from the master hand via the AD converter to conduct gravity compensation for the force torque sensor, calculation of the contact points between fingertips and object, calculation of finger kinematics, calculation of the position and orientation of the grasped object when an object is grasped, calculation of the resultant force and moment acting on the center of gravity of the grasped object, and all coordinate transformation [10]. The data sampling period from the master hand is 1 msec, the period of position and orientation calculation of the grasped object being 15 msec, and periods of other calculation being 1 msec. The AD converter has a low-pass filter built in whose cutoff frequency is 50 Hz.

The non-real-time layer is implemented in a SPARC Station (Solaris 2.6), where human grasping data is recorded, retrieved, displayed, and analyzed.



(a) (b)

(c) (d)

Fig. 6. Fingertips of the master hand, applied force to a sheet of paper and the trajectory of the contact point when an operator puts on the master hand and pick up the paper with the thumb and the index finger.

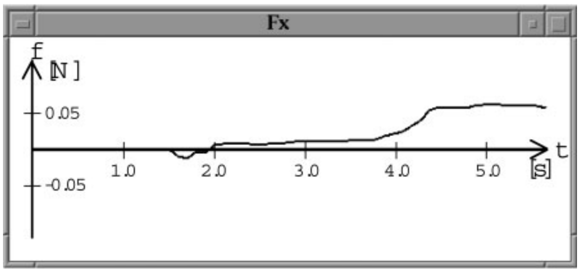
Communication between both levels is conducted by socket communication via the Ethernet.

The master hand is connected to the multifingered robot hand [6] via the Ethernet and it is possible to perform and verify the results of grasping analysis by the robot hand. The master hand and multifingered hand share function routines such as force torque data processing and calculation of position and orientation of the grasped object.

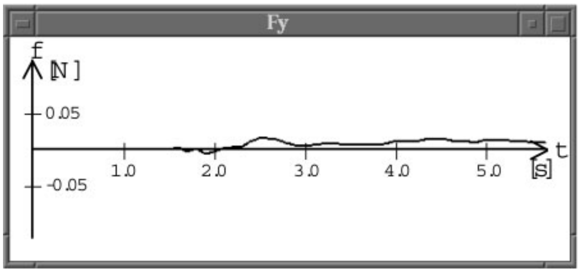
4. Example of Grasping Data Sample

Example data of human grasping captured by the master hand is shown. For demonstration by a human subject, operation is conducted to pick up a sheet of paper on the table with the thumb and index finger. The operator conducts operations while displaying data transmitted from the real-time level. At any given point of the demonstration, recording of grasping operation data is started and terminated. In our experiment, a world frame is set at the contact point of the thumb. The hand frame, position and orientation of each fingertip, contact points between fingertip and object, and contact forces are recorded in the file. The recording time or getting all data into the file is 0.1 sec.

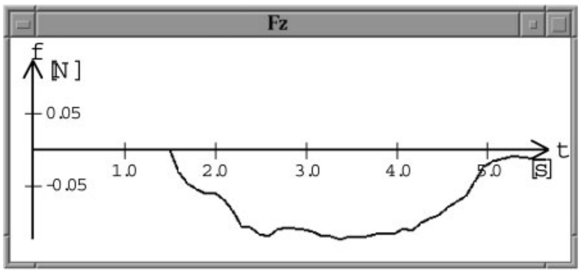
Figure 6 shows contact forces with which the fingers exerted on a sheet of paper, and the trajectory of the contact point of the index finger and orientation of its fingertip. **Fig. 6(a)** is data, when the thumb and index finger are placed on the sheet of paper to start pickup. **Fig. 6(d)**



(a) Fx



(b) Fy



(c) Fz

Fig. 7. The time series plot of the contact force of the index finger when an operator pick up a sheet of paper.

is data, when the sheet of paper is turned up between the thumb and index finger. Since the origin is located at the contact point of the thumb in the display, it appears that the thumb stands still, but the thumb and index finger actually move with similar amounts. **Fig. 7** shows time series data of force the index finger exerted on the sheet of paper. **Fig. 7** uses time as the horizontal axis, although, it is possible to show the change in contact force versus progress of the operation by using the distance between the thumb and index finger as the horizontal axis.

5. Master Hand Features

Since the master hand simultaneously measures fingertip movement and contact force acting thereon, it is possible to determine the relationship between them and thus to determine fingertip impedance.

Since the fingertip of the master hand has the same shape, material, and sensors as those of the robot hand, it enters an equivalent state when the robot hand is placed on the human finger, so the same algorithm of grasping recognition by the robot hand is applied, enabling us to calculate the contact point between the fingertip and object [11], to obtain a geometric model of the grasped object [6], and to monitor the position and orientation of the grasped object [12]. For this reason, grasping data obtained by the master hand can describe the state of the grasped object. From data on human grasping, we calculate the motion of the grasped object and calculate the resultant force and moment acting on the grasped object. Conventional master hand systems measure joint angles of fingers as human operation data. In order to use those human operation data for teaching of the robot hand or remote control, a robot hand should have the same DOF arrangement as the human hand dose. Our master hand obtains movement of the grasping object and resultant force and moment acting on the grasped object, so that it is possible to give a trajectory of the grasped object and target contact force from human operation data. Therefore human operation data obtained by the device can be used by different robot hands. Further, because position and orientation of each fingertip is obtained with respect to the hand frame, conducting calibration of finger size enables us to calculate the joint angle of the human hand [4], and measure the movement of the human hand itself.

6. Conclusions

We developed a master hand, used on the human finger and able to simultaneous measurement of fingertip movement and contact force acting thereon. The master hand consists of serial links measuring fingertip movement and six-axis force/torque sensors able to be put on at the user's fingertip, base, gloves, and inclination sensor. The purpose of the development of the master hand is, when the user is subjected to the same physical restrictions as the robot, to investigate what grasping strategy is conducted and to use the data for developing the control algorithm of the robot hand. The fingertip of the master hand has the same shape, material, and sensor as those of the robot hand. The grasping recognition algorithm of robot hand is applied so data on grasping versus the state of the grasped object is described. We discussed the mechanism of the master hand, the system configuration, examples of the data captured by the master hand, and features of our master hand. In future, we will accumulate and analyze grasping data by using our master hand to develop control algorithms for the robot hand.

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