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A Novel Anthropomorphic Robot Hand and its Master Slave System

Tetsuya Mouri and Haruhisa Kawasaki
Gifu University
Japan

1. Introduction

Future humanoid robots will execute various complicated tasks based on communication with human users. These humanoid robots will be equipped with anthropomorphic robot hands much like the human hand. The robots will eventually supplant human labor in the execution of intricate and dangerous tasks in areas such as manufacturing, space exploration and the seabeds.

Many multi-fingered robot hands (Salisbury & Craig, 1982) (Jacobsen et al., 1984) (Jau, 1995) (Kyriakopoulos et al., 1997) have been developed. These robot hands are driven by actuators in a location remote from the robot hand frame and are connected by tendon cables. Elasticity in the tendon cable causes inaccurate joint angle control, and the long wiring of tendon cables may obstruct the motion of the robot when the hand is attached to the tip of a robot arm. To solve these problems, robot hands in which the actuators are built into the hand (Bekey et al., 1990) (Rosheim, 1994) (Lin & Huang, 1996) (Butterfass et al., 2001) (Namiki et al., 2003) (Yamano et al., 2003) have been developed. However, these hands have the problem that their movement differs from that of the human hand because both the number of fingers and the number of joints in the fingers are insufficient. Recently, many reports (Fearing, 1990) (Howe, 1994) (Shimojo et al., 1995) (Johnston et al., 1996) (Jockusch et al., 1997) have been presented on the use of tactile sensors that attempt to realize adequate object manipulation through contact with the fingers and palm. There has been only the slight development of a hand that combines a 6-axes force sensor attached to the fingertips with a distributed tactile sensor mounted on the hand surface.

To provide a standard robot hand used to study grasping and dexterous manipulation, our group has developed the Gifu Hand I (Kawasaki & Komatsu, 1998) (Kawasaki & Komatsu, 1999), the Gifu Hand II (Kawasaki et al., 1999), the Gifu Hand III (Mouri et al., 2002), and the kinetic humanoid hand (Kawasaki et al., 2004).

This paper presents a novel robot hand called the KH (Kinetic Humanoid) Hand type S for sign language, which requires a high degree of fingertip velocity. In addition, we construct a PC-based master slave system to demonstrate effectiveness in grasping and manipulating objects. An experiment involving grasping and manipulating objects by the master slave control is shown. Our results show that the KH Hand type S has a higher potential than previous robot hands in rendering a picturesque hand shape and performing dexterous object manipulations like the human hand.

2. An Anthropomorphic Robot Hand

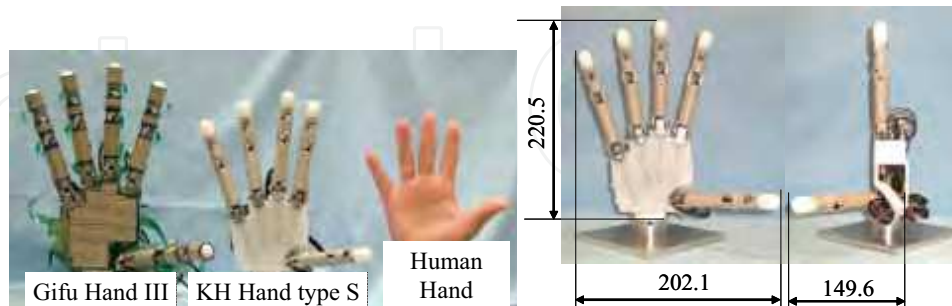


Figure 1. KH Hand type S

Recently, various robot hands with built-in actuators have been developed. However, these hands present the problem that their movement differs from that of the human hand because they have had an insufficient number of fingers and finger joints. To provide a standard robot hand to be used to study grasping and dexterous manipulation, our group developed the Gifu Hand I (Kawasaki & Komatsu, 1998) (Kawasaki & Komatsu, 1999), the Gifu Hand II (Kawasaki et al., 1999), and the Gifu Hand III (Mouri et al., 2002). The design concept for these robot hands was as follows.

1. **Size:** It is desirable that for skillful manipulation the robot hand resemble the human hand in size.
2. **Finger DOF:** The number of joints and the DOF motion in the robot hand are similar to those of the human hand.
3. **Opposability of the thumb:** The robot hand thumb is opposed to the four other fingers, enabling the hand to manipulate objects dexterously like the human hand.
4. **Force sensor:** The robot hand grasps and manipulates objects dexterously with the help of tactile sensors and force sensors in the fingers.
5. **Built-in servomotor method:** The motion of the robot arm is not disturbed by the robot hand, and the robot hand is easily attached to the robot arm.
6. **Unit design of the finger:** Each joint must be modular, and each finger must be a unit in order to realize easy maintenance and easy manufacture of the robot hand.

The Gifu Hand series are 5-finger hands driven by built-in servomotors that have 20 joints with 16 DOF. These hands use commercial motors. The length of the robot hand, in which the actuators are built, depends on the size of the motors. On this basis, we have developed and are presenting the smaller kinetic humanoid hand, which uses prototype brushless motors (Kawasaki et al., 2004). In the older robot hands, the fingertip velocity was slow because their motors had high reduction ratio gears. The shape and freedom of motion of our robot hands are almost equivalent to those of human hands. Therefore, we can use the robot hands not only for grasping and manipulating objects but also as communication tools for such as sign language. Because the drivers for the brushless motor are large and have much hardwiring, it has been difficult to miniaturize and make practicable the kinetic humanoid hand. Therefore, the new robot hand, which can be driven at same speed as a human hand, has been developed based on the use of a commercial DC motor with the kinetic humanoid hand.

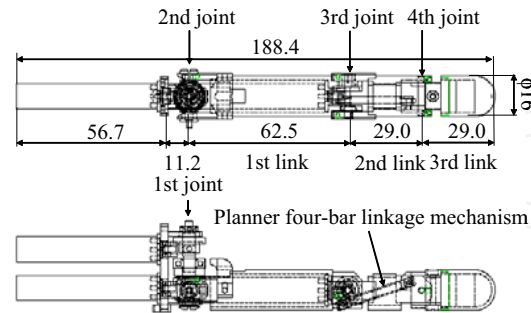


Figure 2. Design of fingers

Weight [kg]	Finger	0.097
	Total	0.619
Length [mm]	Finger	188.4
	Total	220.5
Operating angle of joints [deg]	1st	-20 ~ 20
	2nd	-10 ~ 90
	3rd	-10 ~ 90
	4th	-10 ~ 90
Fingertip force [N]		0.86
Gear ratio	1st	614.1 : 1
	2nd	307.2 : 1
	3rd	134.4 : 1

Table 1. Specifications

2.1 Characteristics

An overview of the developed KH Hand type S is shown in Figure 1. The hand has five fingers. The finger mechanism is shown in Figure 2. The servomotors and the joints are numbered from the palm to the fingertip. Each of the fingers has 4 joints, each with 3 DOF. The movement of the first finger joint allows adduction and abduction; the movement of the second to the fourth joints allows anteflexion and retroflexion. The third servomotor actuates the fourth joint of the finger through a planar four-bar linkage mechanism. The fourth joint of the robot finger can engage the third joint almost linearly in the manner of a human finger. All five fingers are used as common fingers because the hand is developed for the purpose of expressing sign language. Thus, the hand has 20 joints with 15 DOF. Table 1 summarizes the characteristics of KH Hand type S. The weight of the hand is 0.656 kg, and the bandwidth for the velocity control of the fingers is more than 15 Hz, which gives them a faster response than human fingers. The dexterity of the robot hand in manipulating an object is based on thumb opposability. The thumb opposability (Mouri et al., 2002) of the robot hand is 3.6 times better than that of the Gifu Hand III. To enable compliant pinching, we designed each finger to be equipped with a six-axes force sensor, a commercial item. Tactile sensors (distributed tactile sensors made by NITTA Corporation) are distributed on

the surface of the fingers and palm. The hand is compact, lightweight, and anthropomorphic in terms of geometry and size so that it is able to grasp and manipulate like the human hand. The mechanism of KH Hand type S is improved over that of the kinetic humanoid hand, as described in the next section.

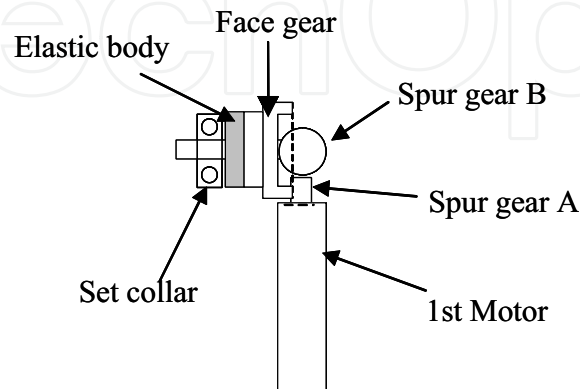


Figure 3. Reduction of backlash

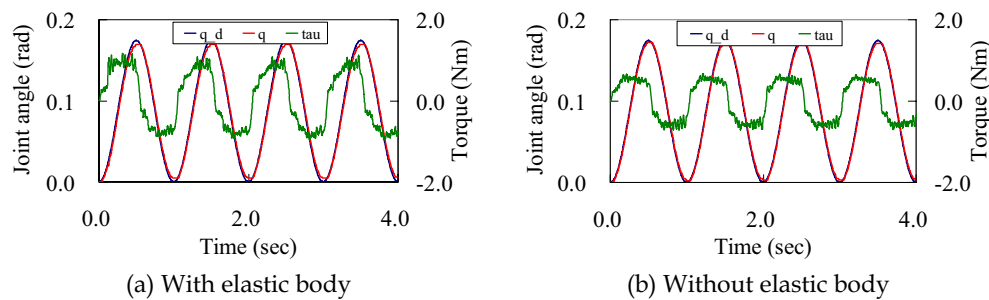


Figure 4. Effects of elastic body

2.2 Weight Saving

The weight of Gifu Hand III and the kinetic humanoid hand are 1.4 and 1.09 kg, respectively. The major part of the weight of Gifu Hand III is the titanium frame of the fingers. Therefore, the new KH Hand type S uses a plastic frame for the fingers and palm, and its weight is 0.61 times lighter than that of the older kinetic humanoid hand.

2.3 Motors

The Gifu Hand III has been developed with an emphasis on fingertip forces. High output motors have been used, with the hand's size being rather larger than that of the human hand. In order to miniaturize the robot hand, compact DC motors (the Maxson DC motor, by Interelectric AG), which have a magnetic encoder with 12 pulses per revolution, are used in the new robot hand. The diameter of servomotors was changed from 13 to 10 mm. The fingertip force of KH Hand type S is 0.48 times lower than that of the Gifu Hand III and has a value of 0.86 N. At the same time, its fingertip velocity is higher.

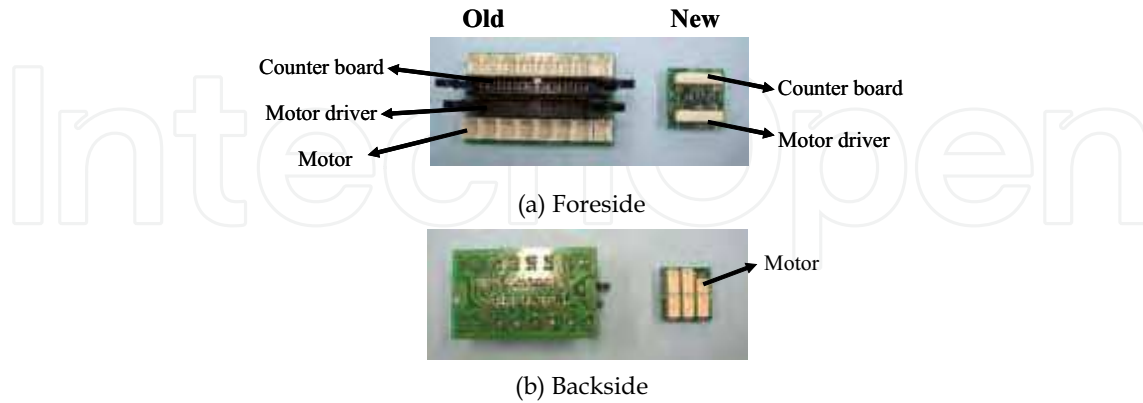


Figure 5. Transfer substrate

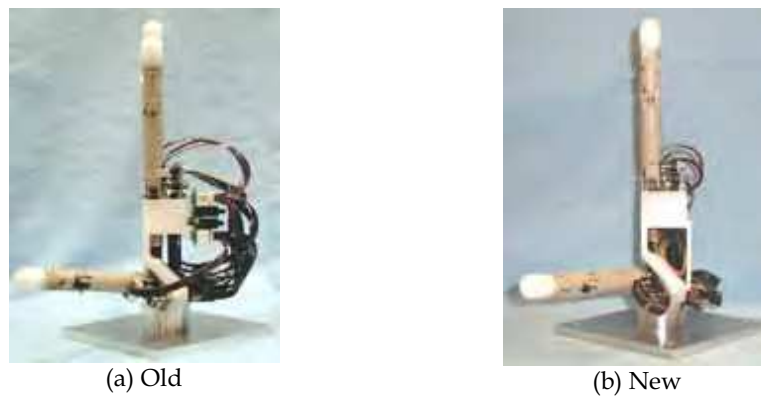


Figure 6. Over view with transfer substrate

2.4 Reduction of Backlash in the Transmission

The rotation of the first and second joints is controlled independently through an asymmetrical differential gear by the first and second servomotors. The backlash of the first and second joints depends on the adjustment of the gears shown in Figure 3. The lower the backlash we achieve, the higher becomes the friction of the gears transmission. An elastic body, which keeps a constant contact pressure, was introduced between the face gear and spur gears to guarantee a low friction. The effects of the elastic body were previously tested in Gifu Hand III, with the experimental results shown in Figure 4. Both the transmissions with and without the elastic body were accommodated at the same level. A desired trajectory is a sine wave, and for that the joint torque is measured. Figure 4 shows that the root mean joint torques without and with the elastic bodies were 0.72 and 0.49 Nm, respectively. Hence, the elastic body helps to reduce the friction between the gears.

2.5 Transfer Substrate

The robot hand has many cables, which are motors and encoders. The transfer substrate works the cables of counter boards and a power amp of the driving motors that are connected to the motors that are built in the fingers. Therefore, a new transfer substrate was

developed for downsizing. Figure 5 shows the foreside and backside of the developed transfer substrate, which is a double-sided printed wiring board. The pitch of the connectors was changed from 2.5 to 1.0 mm. Compared with the previous transfer substrate, the weight is 0.117 times lighter and the occupied volume is 0.173 times smaller. Figure 6 shows an overview of a KH Hand type S equipped with each transfer substrate. As a result of the change, the backside of the robot hand became neat and clean, and the hand can now be used for the dexterous grasping and manipulation of objects, such as an insertion into a gap in objects.

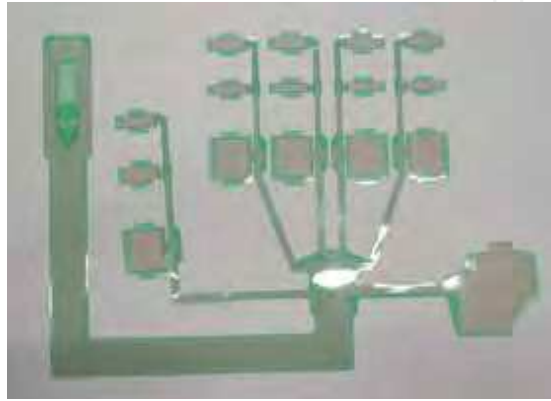


Figure 7. Distributed tactile sensor

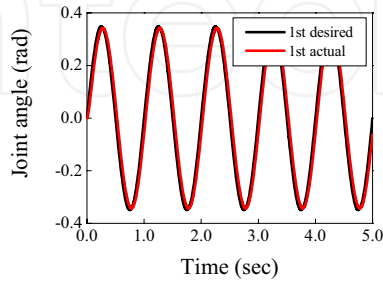
Number of detecting points	
Total	895
Palm	321
Thumb	126
Finger	112
Maximum load [N/m ²]	2.2x10 ⁵
Electrode column width [mm]	2.55
Electrode row width [mm]	3.35
Column pitch [mm]	3.40
Row pitch [mm]	4.20

Table 2. Characteristic of distributed tactile sensor

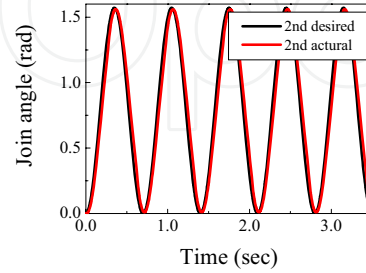
2.6 Distributed Tactile Sensor

Tactile sensors for the kinetic humanoid hand to detect contact positions and forces are mounted on the surfaces of the fingers and palm. The sensor is composed of grid-pattern electrodes and uses conductive ink in which the electric resistance changes in proportion to the pressure on the top and bottom of a thin film. A sensor developed in cooperation with the Nitta Corporation for the KH Hand is shown in Figure 7, and its characteristics are shown in Table 2. The numbers of sensing points on the palm, thumb, and fingers are 321,

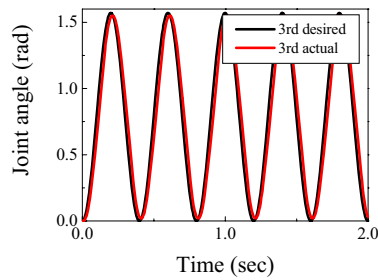
126 and 112, respectively, with a total number of 895. Because the KH Hand has 36 tactile sensor points more than the Gifu Hand III, it can identify tactile information more accurately.



(a) 1st joint



(2) 2nd joint



(c) 3rd joint

Figure 8. Trajectory control

2.7 Sign Language

To evaluate the new robot hand, we examined control from branching to clenching. Figure 8 shows the experiment results. The result means that the angle velocity of the robot hand is sufficient for a sign language.

Sign language differs from country to country. Japanese vocals of the finger alphabet using the KH Hand type S are shown in Figure 9. The switching time from one finger alphabet sign to another one is less than 0.5 sec, a speed which indicates a high hand shape display performance for the robot hand.

3. Master Slave System

In order to demonstrate effectiveness in grasping and manipulating objects, we constructed a PC-based master slave system, shown in Figure 10. An operator and a robot are the master and slave, respectively. The operator controls the robot by using a finger joint angle, hand position and orientation. The fingertip force of the robot is returned to the operator, as shown in Figure 11. This is a traditional bilateral controller for teleoperations, but to the best of our knowledge no one has previously presented a bilateral controller applied to a five

fingers anthropomorphic robot hand. In general, in a master slave system, a time delay in communications must be considered (Leung et al., 1995), but since our system is installed in a single room, this paper takes no account of the time delay.

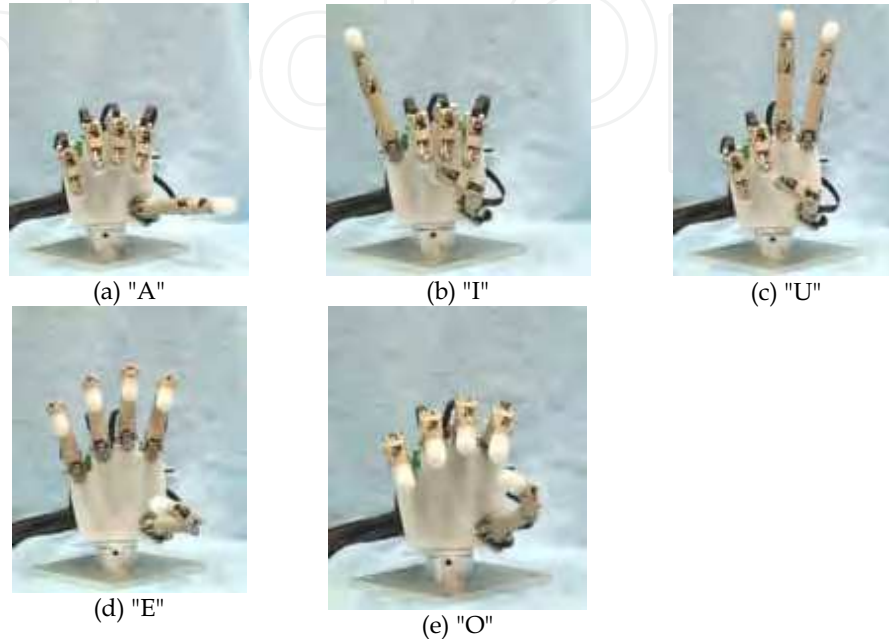


Figure 9. Japanese finger alphabet

3.1 Master System

The master system to measure the movement of the operator and to display the force feeling is composed of four elements. The first element, a force feedback device called a FFG, displays the force feeling, as will be described in detail hereinafter. The second is a data glove (CyberGlove, Immersion Co.) for measuring the joint angle of the finger. The third is a 3-D position measurement device (OPTOTRAK, Northern Digital Inc.) for the hand position of operator and has a resolution of 0.1 mm and a maximum sampling frequency of 1500 Hz. The fourth element is an orientation tracking system (InertiaCube2, InterSense Inc.) for the operator's hand posture; the resolution of this device is 3 deg RMS, and its maximum sampling frequency is 180 Hz. The operating system of the PCs for the master system is Windows XP. The sampling cycle of the FFG controller is 1 ms. The measured data is transported through a shared memory (Memolink, Interface Co.). The hand position is measured by a PC with a 1 ms period. The sampling cycle of the hand orientation and the joint angle is 15 ms. The FFG is controlled by a PI force control. Since sampling cycles for each element are different, the measured data are run through a linear filter.

The developed robot hand differs geometrically and functionally from a human hand. A method of mapping from a human movement to the command of the robot is required, but our research considers that the operator manipulates the system in a visceral manner. The joint angle can be measured by the data glove, so that this system directly transmits the joint data and the hand position to the slave system, as we next describe.

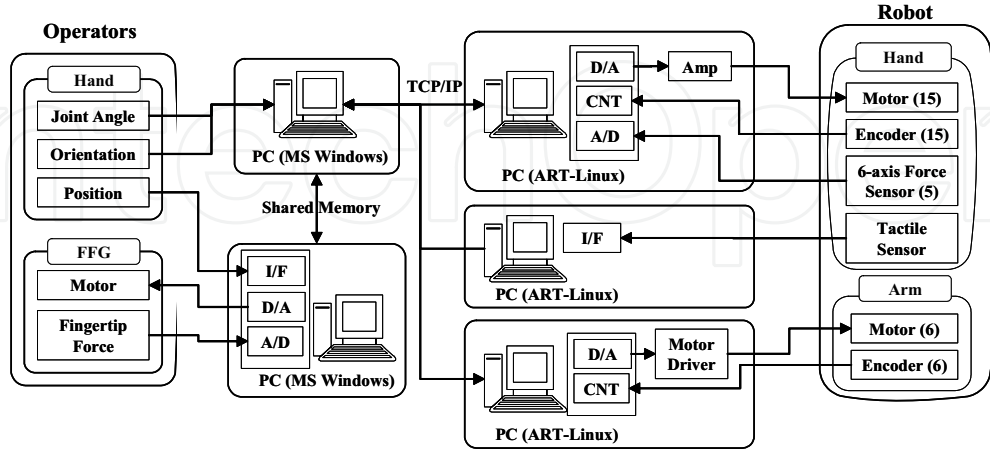


Figure 10. Control system

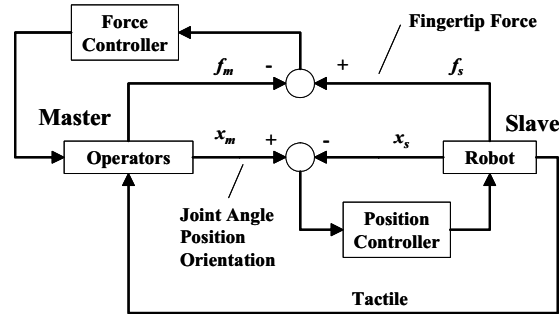


Figure 11. Master slave system

3.2 Slave System

The slave system consists of a hand and an arm. The robot hand is the developed KH Hand type S equipped with the 6-axes force sensor (NANO 5/4, BL. AUTOTEC Co.) at each fingertip and the developed tactile sensor. The robot arm is the 6-DOF robot arm (VS6354B, DENSO Co.). The operating system of the PCs for the slave system is ART-Linux, a real-time operating system (Movingeye, 2001). The tactile sensor output is processed by a PC with a 10 ms period. The measured tactile data is transported to a FFG control PC through TCP/IP. The sampling cycle of the hand and arm controller is 1 ms. Both the robot arm and hand are controlled by a PD position control.

3.3 Force Feed Back Glove

The forces generated from grasping an object are displayed to the human hand using the force feedback glove (FFG), as shown in Figure 12 (Kawasaki et al., 2003). The operator attaches the FFG on the backside of the hand, where a force feedback mechanism has 5 servomotors. Then the torque produced by the servomotor is transmitted to the human fingertips through a wire rope. The fingertip force is measured by a pressure sensitive conductive elastomer sensor (Inaba Co). A human can feel the forces at a single point on

each finger, or on a total of 5 points on each hand. The resolution of the grasping force generated by the FFG is about 0.2 N. The force mechanism also has 11 vibrating motors located in finger surfaces and on the palm to present the feeling at the moment that objects are contacted. A person can feel the touch sense exactly at two points on each finger and at one point on the palm, or at a total of 11 points on each hand.

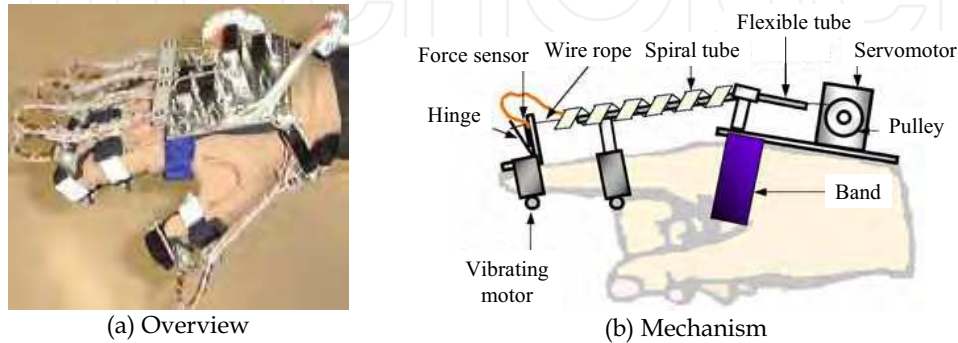


Figure 12. Force feedback glove

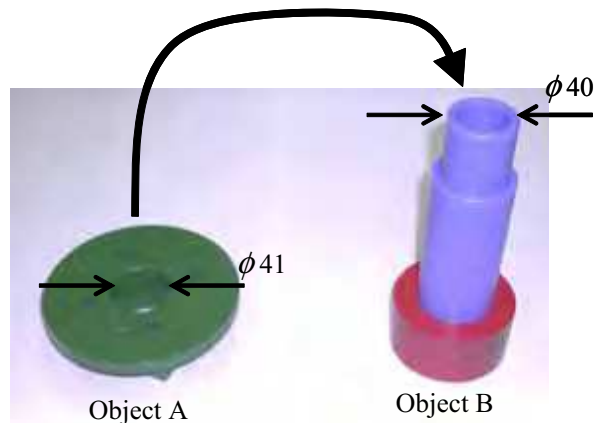


Figure 13. Peg-in-hole task

4. Experiment

4.1 Peg-in-hole task

As shown in Figure 13, a peg-in-hole task was conducted because it is the most fundamental assembly operation. We used two objects: a disk with a hole (A) and a cylinder (B). The weight of object A is 0.253 kg, the outer diameter is 0.13 m, and the hole's diameter is 0.041 m. The weight of object B is 0.198 kg, and the diameter is 0.040 m. The clearance between object A and B is 0.001 m.

The peg-in-hole task sequence is as follows. The robot (operator) approaches an object A, grasps the object, translates it closely to object B, and inserts it into object B.

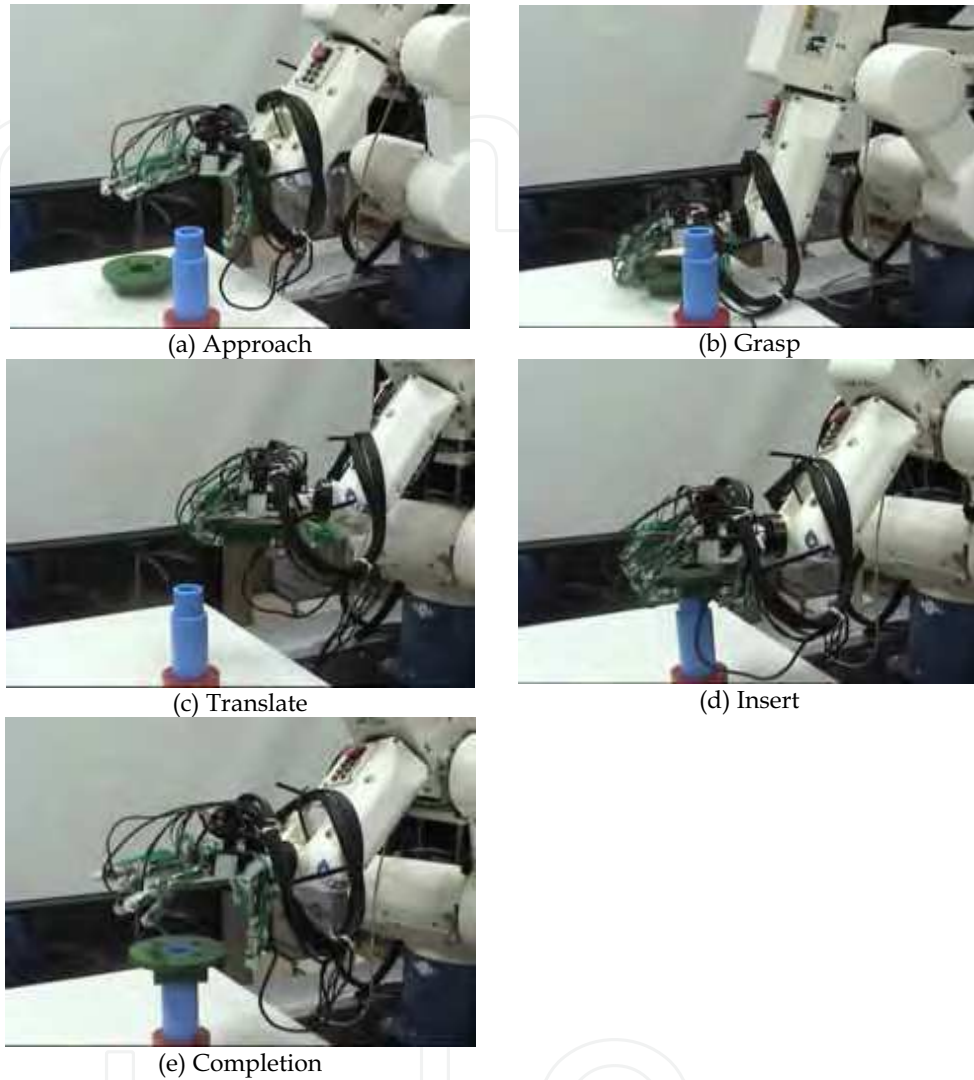


Figure 14. Sequence of peg-in-hole task

4.2 Experimental Result

Experimental results of the peg-in-hole task controlled by the master slave system are shown in Figure 14. Figures 15 and 16 show the joint angles and the position and orientation of the robot hand. We used the KH Hand types with the previous transfer substrate in this experiment. They indicate that the controlled variables are close to the desired ones. These results show that the KH Hand type S can perform dexterous object grasping and manipulation like the human hand.

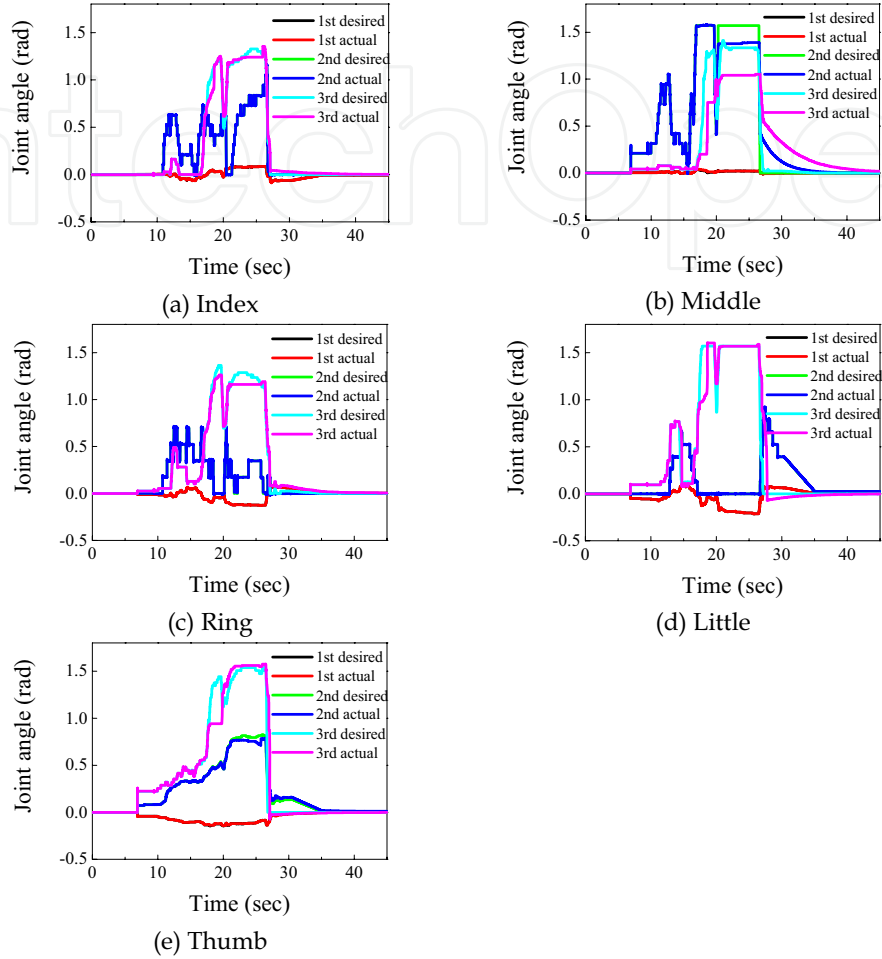


Figure 15. Joint angle of robot hand

5. Conclusion

We have presented the newly developed anthropomorphic robot hand named the KH Hand type S and its master slave system using the bilateral controller. The use of an elastic body has improved the robot hand in terms of weight, the backlash of the transmission, and friction between the gears. We have demonstrated the expression of the Japanese finger alphabet. We have also shown an experiment of a peg-in-hole task controlled by the bilateral controller. These results indicate that the KH Hand type S has a higher potential than previous robot hands in performing not only hand shape display tasks but also in grasping and manipulating objects in a manner like that of the human hand. In our future work, we are planning to study dexterous grasping and manipulation by the robot.

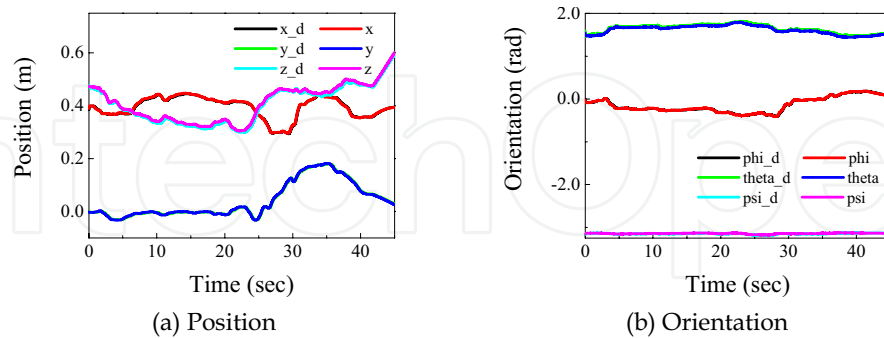


Figure 16. Joint angle of robot arm

6. Acknowledgment

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Humanoid Robots, Human-like Machines

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In this book the variety of humanoid robotic research can be obtained. This book is divided in four parts: Hardware Development: Components and Systems, Biped Motion: Walking, Running and Self-orientation, Sensing the Environment: Acquisition, Data Processing and Control and Mind Organisation: Learning and Interaction. The first part of the book deals with remarkable hardware developments, whereby complete humanoid robotic systems are as well described as partial solutions. In the second part diverse results around the biped motion of humanoid robots are presented. The autonomous, efficient and adaptive two-legged walking is one of the main challenge in humanoid robotics. The two-legged walking will enable humanoid robots to enter our environment without rearrangement. Developments in the field of visual sensors, data acquisition, processing and control are to be observed in third part of the book. In the fourth part some "mind building" and communication technologies are presented.

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51000 Rijeka, Croatia
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
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