Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Development of a Robot Finger for Five-fingered Hand using Ultrasonic Motors

Ikuo Yamano*, Kenjiro Takemura**and Takashi Maeno***

Department of Mechanical Engineering
Keio University, Yokohama 223-8522 JAPAN
tel/fax: +81-45-566-1516
e-mail: *i-yamano@mmm-keio.net, **kenjiro@mmm-keio.net, *** maeno@mech.keio.ac.jp

Abstract

A robot finger is developed for five-fingered robot hand having equal number of DOF to human hand. The robot hand is driven by a new method proposed by authors using ultrasonic motors and elastic elements. The method utilizes restoring force of elastic element as driving power for grasping an object, so that the hand can perform the soft and stable grasping motion with no power supply. In addition, all the components are placed inside the hand thanks to the ultrasonic motors with compact size and high torque at low speed. Applying the driving method to multi-DOF mechanism, a robot index finger is designed and implemented. It has equal number of joints and DOF to human index finger, and it is also equal in size to the finger of average adult male. The performance of the robot finger is confirmed by fundamental driving test.

1. Introduction

Human being has been developing variety of robots. Before the 1970s, the Industrial robots for simple work in plant were mainly developed. Then, the robots have been improved and multi-functionalized with the progress of technology. Recently, they have extended their fields and uses. Particularly, the humanoid robot technology attracts high attention of public. The humanoid robot has high flexibility, so they can work in human environment. The manlike robots such as the humanoid robot are expected to realize novel concepts as tele-existence and coexistence of the human being and the robot.

Human being usually contacts with the external environment with his hand. The robot also needs the hand as the end-effecter to interact with the object. The robot hand is divided into three categories: mechanical gripper, special purpose hand, and universal hand [1]. The former two types are for the limited use, so their form is not generally manlike. They are often used for industrial robots. On the other hand, the humanoid robot has the last type of robot hand because it requires to grasp and handle the various types of objects steadily and smoothly. The universal hand can also be used for other purposes such as tele-operation in space environment and in hazardous environment and tele-surgery. Therefore, the development of universal robot hand has been an interesting topic among researchers, and a lot of sophisticated robot hands have indeed developed all over the world [2-7].

Here, we divide the robot hands into two types; (1) built-in actuator type and (2)external actuator type. The former type of robot hand generates the motion of fingers by using motors installed inside the finger or the palm. For example, the dexterous hand for WENDY [2] and DLR II [3] are classified as this type. In this type, DC motor or AC motor with the reduction gear-head is usually utilized as the actuator. This type of robot hand has merit that the hand can be used with various types of robot arms because the robot hand has independent structure. On the other hand, there are some demerits. The most serious one is the limitation on size. Generally, universal robot hand imitates the structure of human hand since the design of structure and the operation with master-slave system are simple in that way. However, most of built-in actuator type robot hands have equal to or less than four fingers. Those with five fingers have less number of joints or DOF than human hand. There is other argument whether the robot hand needs equal function to human hand or not, but we venture to argue that the lack of the number of fingers, joints, or DOF aggravates the stability of grasping and variety of handling. In addition, this type of robot hand has heavy fingers and backlash of joint because of motors with reduction gear-head in the finger part, which makes the controllability worse.

On the other hand, the latter type, external actuator type, makes the structures of their fingers simple and light by using wire or belt driven mechanism. For example, Utah/M.I.T hand [4], Robonaut hand [5], and the shadow hand [6] are classified as this type. This type has the following merits. First, by setting high power actuator like air pressure actuator, the output force becomes very large. Second, the structural limitation of the finger part becomes smaller, so the design of mechanism with a large number of DOF becomes possible. For example, the shadow hand has 21 DOF which is equal to human hand. However, since this type of hand must be connected to external actuator mechanically, it is difficult to be used with various robot arms, and the movable area of hand becomes limited, which results in poor flexibility.

As shown above, both types of robot hands have problems in the respect of structure, performance, and flexibility. Therefore, this research aims at development of a five-fingered robot hand with high performance and flexibility as human hand. In the present study, we develop a robot finger using ultrasonic motors as the first step of the development of a full robot hand. The robot finger has equal number of joints and DOF to human index finger, and performs stable grasping motion by using a novel driving method. In addition, the robot finger has compliance against external force, light weight and independent structure.

The basic design of robot hand, the driving method using ultrasonic motor and elastic elements, the driving mechanism of robot finger, and its detailed design are described in chapter 2. Next, the implementation and the experiment are described in chapter 3. Finally, the conclusions and future works are presented in chapter 4, where usefulness of this novel robot finger is evaluated.

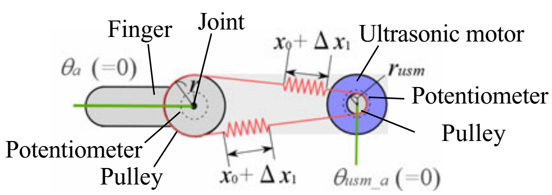
2. Design

2.1 Basic Design

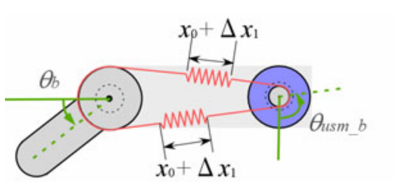
At first, we describe the basic design of our robot hand. As described in chapter 1, we think that the structure of the robot hand ought to be equal to human hand, because of its flexibility against the environment, facility of operation with master-slave system, and stability of grasping motion. Therefore, our robot hand has five fingers and four DOF per each finger. Moreover, we make the weight of the robot hand no more than 1 kg considering the connection to robot arm.

As described in chapter 1, each of the two types of robot hand has problem. Here, we take advantage of only merits of two types of robot hand in designing our robot hand. That is, we arrange all the actuators inside the palm of robot hand, and generate the motion by wire driven mechanism. The robot hand has independent structure with five fingers alleviating design limitation of finger part by using wire driven mechanism. In order to set all actuators inside the palm, we adopt the ultrasonic motor as actuator. The ultrasonic motor has features such as high driving torque at low rotational speed, compact size and light weight. Therefore, it is suitable for the actuator of robot hand that has structural restriction. Moreover, the driving method presented in the next section utilizes the feature of high holding torque of ultrasonic motor. In addition, the excellent response with no backlash is expected since the ultrasonic motor does not require high reduction ratio and it has high responsiveness.

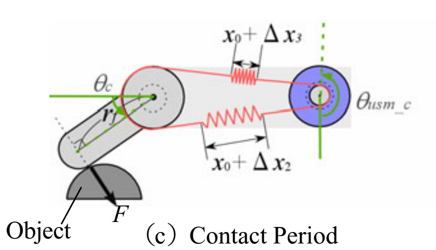
In our robot hand, we divide robot hand into five finger units considering the facility of improvement and maintenance. In this paper, we develop a robot finger corresponding to human index finger.



(a) Initial condition



(b) Non-contact period



(c) Contact Period

Figure 1: *Outline of driving method described using 1 DOF finger model*

2.2 Driving Method

In this section, we describe our wire driving method. The wire driving mechanism needs N, N+1 or 2N actuators for N DOF motion. N actuators type has merits in respect of arrangement of motor, driving efficiency, and facility of control. However, it is difficult to adjust initial tension in wire. Moreover, the wire often becomes loose. Beside, N+1 type and 2N type are able to adjust initial tension by output torque of motor. Salisbury Hand is an example of N+1 type [7], and Utah/M.I.T hand is an example of 2N type. However, it is difficult to implement a lot of motors inside the hand.

Then, we adopt a new driving method as shown in Fig. 1. This outline represents the MP joint model of human finger. It contains two elastic elements with spring coefficient of k inside a wire, and an ultrasonic motor. The ends of wire are fixed to two pulleys. The rotational angular positions of joint and motor are measured by potentiometers. In initial condition (a), two elastic elements are preloaded with Δx_1 elongation from initial length, x_0. It results in the tension at the wire represented by $k \cdot \Delta x_1$. Therefore, this method enables us to simply adjust the initial wire tension by the initial length of elastic element. Furthermore, the joint has passive compliance against the external force because of elastic element. The value of compliance depends on the spring coefficient. This soft mechanism brings the robot hand the adaptability against the environment, and avoids the damage on the object during the grasping motion.

When the ultrasonic motor rotates counterclockwise, the joint also rotate in the same direction. If we assume that the inertia of finger is small enough, and the elastic elements are not extended by inertia, the relationship between radii of pulleys and angular positions is given by the following equation during the non-contact period (b).

$$r \cdot \theta_b = r_{usm} \cdot \theta_{usm\_b} \tag{2.1}$$

Then, when the finger gets in contact with any object, the equation (2.1) is not valid because the elastic elements deform. During the contact period (c), the output force F caused by the difference of two elastic elements is given to the object. In this period, the relationship between radii of pulleys and angular positions and output force is given by the following equation considering the balance of moment.

$$F \cdot r_f = 2 \cdot k \cdot (r_{usm} \cdot \theta_{usm\_c} - r \cdot \theta_c) \cdot r \tag{2.2}$$

In this equation, r_f represents the length of moment arm that is assumed to be definite. By the equation (2.2), the value of the contact force F is calculated by measuring two angular positions, θ and θ_{usm}. Thus, the construction of the input-output system becomes simple because the driving system requires no force sensor. In addition, the force control of the finger is conducted by the position control of the ultrasonic motor. It is difficult for us to control the torque of ultrasonic motor because of its non-linearity of characteristic while it is easy to determine the position exactly because of its high holding torque. Therefore, it can be said that this method take advantage of the feature of ultrasonic motor.

Furthermore, this method makes use of high holding torque of ultrasonic motor in other way. That is, during the contact period (c), the finger can continue to give the steady output force against the object with no power supply to motor, because the high holding torque of ultrasonic motor holds the length of elastic elements. Thus, by using restoring force as output force, the finger can perform efficiently in the respect of power consumption. In addition, with the ultrasonic motor with no reduction gear with high friction, it is easy to conduct active compliance control, where the hand can perform the smooth and stable grasping motion.

2.3 Driving Mechanism

Next, we introduce the driving mechanism of robot finger. The human finger has three joints, MP joint, PIP joint, and DIP joint from the palm side to fingertip, respectively. Each joint generates bend-stretch motion. In addition, the MP joint also generates adduction-abduction motion. Thus, each finger from the index finger to little finger has four DOF.

In order to imitate this structure, we decide the basic arrangement of DOF and joint names of robot finger as shown in Fig. 2. Then, on the premise that we use ring type ultrasonic motor, we design the driving mechanism as shown in Fig. 3. Since the ring type ultrasonic motor is thin compared to other type of motor, the ultrasonic motor 1-3 can be placed parallel to the finger. The ultrasonic motor 1-4 generate the motion of MP1, PIP, DIP and MP2 joint, respectively. The rotational angular positions of four joints and four motors are measured by eight potentiometers respectively.

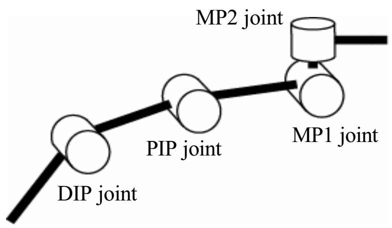


Figure 2: *Arrangement of DOF of finger*

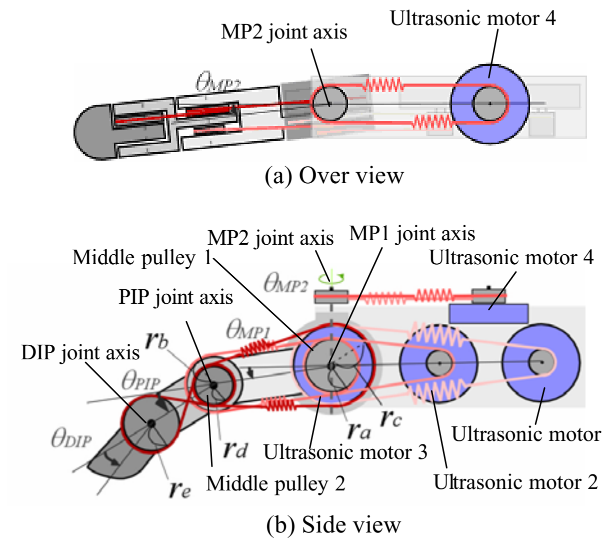


Figure 3: *Outline of driving mechanism*

Above-mentioned driving method is applied to the driving mechanism of MP joint directly. The mechanism of PIP and DIP joints utilize middle pulleys 1 and 2 to make the wire go through other joint axis. Middle pulleys are aligned along the joint axes with small friction using ball bearings. Therefore, when the DIP joint is driven by the ultrasonic motor 3, other joints are not affected by the driving torque. When the MP1 joint is driven by the ultrasonic motor 1, the relationship between $\Delta\theta_{MP1}$ and $\Delta\theta_{PIP}$ is given by the following equation because the wire between MP1 and PIP joints works like parallel link provided that $r_a = r_b$.

$$\Delta\theta_{PIP} = -\Delta\theta_{MP1} \tag{2.3}$$

At the same time, the relationship between $\Delta\theta_{MP1}$ and $\Delta\theta_{DIP}$ is given by the following equation.

$$r_d \cdot \Delta\theta_{DIP} = (r_e - r_c) \cdot \Delta\theta_{MP1} \tag{2.4}$$

When the PIP joint is driven by the ultrasonic motor 2, the MP1 joint is not affected by the driving torque, and the relationship between $\Delta\theta_{PIP}$ and $\Delta\theta_{DIP}$ is given by the following equation because the wire is strained across.

$$r_e \cdot \Delta\theta_{DIP} = r_d \cdot \Delta\theta_{PIP} \tag{2.5}$$

It is known that the PIP and DIP joints of the human finger bend together in a particular rate during the non-contact motion. The equation (2.5) shows that our robot finger realizes this coupled motion between PIP and DIP joints by using one motor, ultrasonic motor 2. It has advantage in

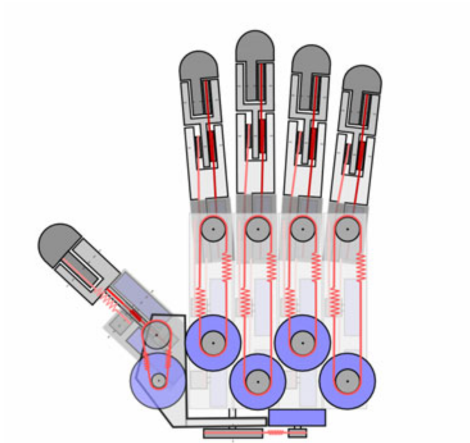


Figure 4: *Outline of five-fingered robot hand*

the respect of power efficient in non-contact free motion.

As presented above, all the relationships among the joints in the motion by one motor are represented by equations. Thus, in controlling the robot finger, the influence of the non-linear interference among the motor's driving torque can be eliminated by giving the input signal considering above relationships.

In addition, adduction-abduction motion is generated by ultrasonic motor 4 using the driving method described in section 2.2. The motor drives the whole finger part together with ultrasonic motor 3 as shown is Fig. 3 (a). Because the base plate with ultrasonic motors 1, 2 and 4 are fixed, there is little structural interference with fingers next to it.

The outline of five-fingered robot hand assembling this robot fingers is shown in Fig. 4, where the thumb is designed with extra DOF.

2.4 Detailed Design

In this section, we explain the detailed design of robot finger based on the driving mechanism presented in section 2.3. First, we decide the ultrasonic motor and the potentiometer arranged in the finger. The ultrasonic motor (SHINSEI USR-30-S4) has the maximum torque of 0.1 Nm, the diameter of 30 mm and the thickness of 10mm. The design for a robot finger corresponding to human index finger is shown in Fig. 5. The measurements of each finger part are decided based on the data of average Japanese adult male [8]. Likewise, the movable ranges of joints are decided to match with the human finger. Table 1 shows movable range of each joint.

Angular positions except for ultrasonic motors 1 and 2 are measured by potentiometers aligned in the same axes with motors. On the other hand, the potentiometers for ultrasonic motors 1 and 2 are located remotely from motor axes because rotational angular positions of these two motors become exceed 360 deg. The axes of potentiometer and ultrasonic motor are connected by rubber belt as shown in Fig. 5.

For the precision grasp, we set the reference position that the finger is grasping the pillar with radius of 25 mm. Then, we decide radii of pulleys to output the force of 6 N with maximum torque from fingertip to the object at the reference position. Then, we decide the rate between r_e and r_d to be 10:7 to correspond the motion of human finger.

3. Implementation and Experiment

3.1 Implementation of robot finger

Next, the robot index finger is implemented based on the design as shown in Fig. 5. The external view of robot finger is shown in Fig. 6. The base plate and pulleys are made of aluminum considering the strength, and the side plate and the finger part are made of acrylic plate for the reduction of weight. For drive wire, we use the metal wire with diameter of 0.27 mm. From the result of calibration, the potentiometers (MURATA PVS1-103A01) have the resolution of about 2 deg.

As shown in Fig.5, the width of each finger is 20 mm, so the width of five-fingered hand becomes about 80 mm

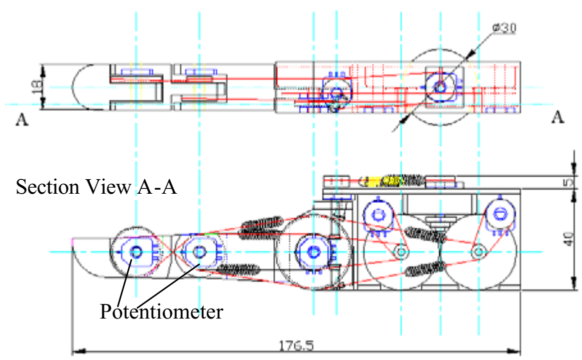


Figure 5: *Detailed design of index finger*

Table 1: *Movable ranges of joints*

DIP joint	0～90
PIP joint	0～100
MP1 joint	-30～80
MP2 joint	-10～30

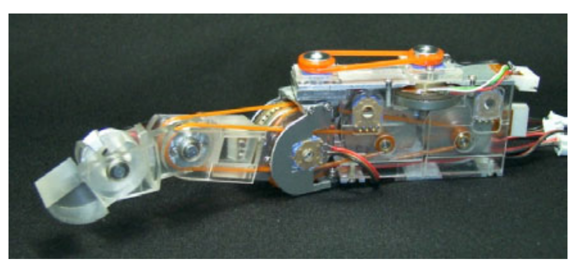


Figure 6: *Picture of developed index finger*

(Fig.4) which is nearly equal to human hand. The weigh of the robot finger is 153 g. Therefore, the whole weight of the hand becomes below 1 kg. It satisfies the specification of the basic design described in section 2.1.

For the elastic element, the use of coil spring or the elastic material such as rubber is conceivable. The coil spring has excellent linearity in the relationship between the force and the displacement, and it has less viscosity. Owing to its size, however, it is difficult to arrange the coil spring inside the space of the finger to get the output force of 6 N. Here, we use rubber for the elastic element. Though rubber has non-linearity, it can be revised by the control. Moreover, rubber generally has the viscosity. However, the joint is exposed to danger of oscillatory force from the elastic element. Therefore, a certain measure of viscosity is effective for the restrain of oscillation.

We think the silicone rubber is suitable for the elastic element because it has little hysteresis. However, the connection between wire and rubber needs more consideration, so the present robot finger utilizes urethane rubber belt in place of silicone rubber and wire.

3.2 Experiment

To evaluate the driving mechanism, the experiment was conducted. First, the control system was constructed. The robot finger is connected with the control PC through the D/A and A/D converter, and the ultrasonic motor utilizes external motor driver. The schematic view of control system is shown in Fig. 7. The whole system becomes simple because it needs no force sensor as explained in section 2.2. In the experiment, the step response of the system and the response of the master-slave system were examined.

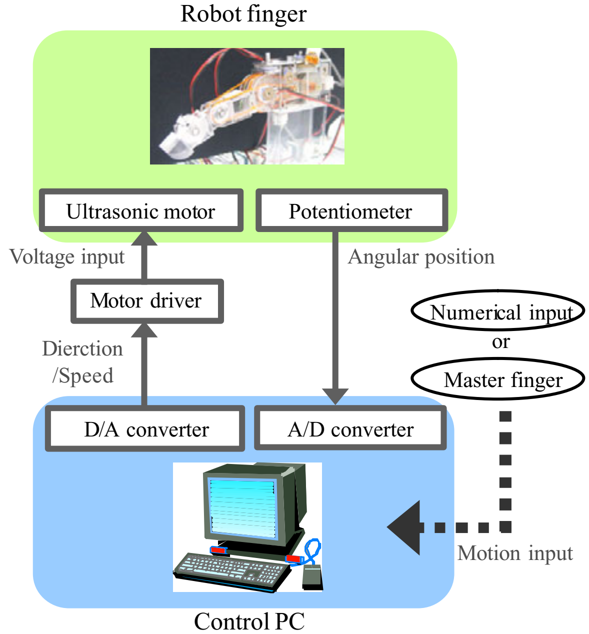


Figure 7: *Outline of control system*

(a) Step response of system

The step response of the system in the position control was examined by giving the numerical input. The initial angular positions of MP1, PIP, and DIP joint were set as 0 deg, and MP2 was set as 30 deg (in the coordinate of Fig. 3). Then, the step inputs of 20, 0, 60 and 40 deg were given to MP1, MP2, PIP and DIP joints, respectively. For controlling the velocity of ultrasonic motor, a proportional feedback controller,

$$V^p = K^p \cdot (\theta_d - \theta) + n \qquad (3.1)$$

was used, where, θ is angular position of joint, θ_d is angular position of step input, V^p is a command voltage for the ultrasonic motor driver which determines the rotational speed of the motor from 0 rpm to 300 rpm, K^p is a proportional feedback gain, and n is a bias for the position feedback control. K^p and n are optimized in order to shorten the settling time.

Fig. 8 shows the results from step response test. As shown in the result, though a little oscillation due to the deformation of elastic element is generated, all the angles of joints reach at the target angles in about 380 msec. The oscillation can be restrained and the settling time can be less than 100 msec by increasing the spring coefficient of the elastic element, because the finger is driven semi-directly by ultrasonic motors capable of generating large torque.

(b) Response of master-slave system

Next, the response of the master-slave system was examined. We utilized implemented robot finger as the slave finger, while we developed a simple master finger with four links and four DOF which directly measures four angular positions of index finger's joints. Fig. 9 shows the view of master slave system. For controlling the velocity of ultrasonic motor, a proportional feedback controller,

$$V^p = K^p \cdot (\theta_m - \theta) + n \qquad (3.2)$$

was used, where, θ_m is angular position of master finger, and the others are same as equation (3.1). K^p and n are optimized in order to shorten the time-lag and restrain the

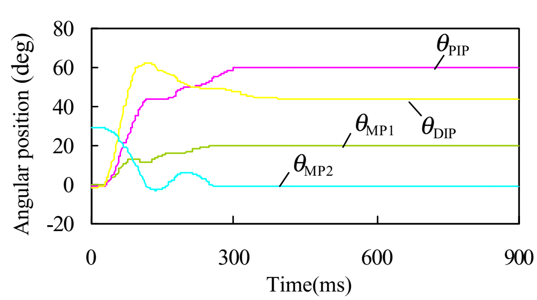


Figure 8: *Step response of angular positions*

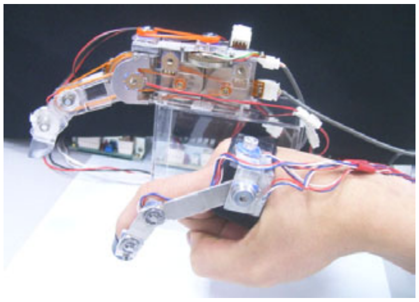


Figure 9: *View of master-slave system*

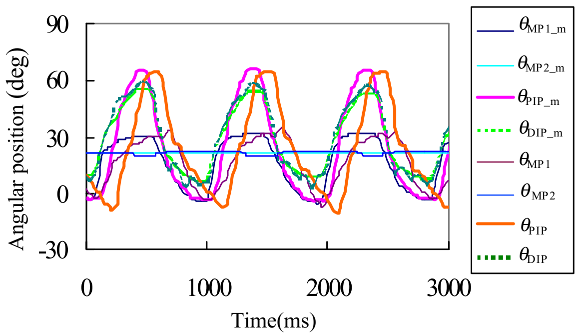


Figure 10: *Trajectory of master-slave system*

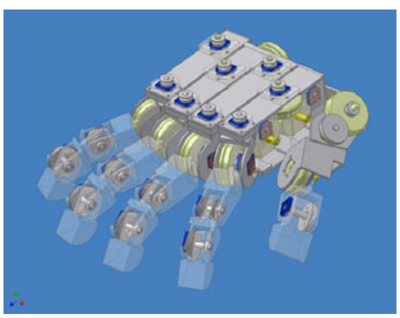


Figure 11: *Detailed design of five-fingered robot hand*

oscillation of the system.

Fig. 10 shows the result of the experiment with the master-slave system. There is little oscillation, and all the angular positions of the slave finger successfully follow those of the master finger with time-lag of 200 msec. The speed of the motion appears to be rapid enough for the practical use. Furthermore, the response can be improved by using controller considering the relationship presented in section 2.3.

In the future, we are planning to develop a five-fingered robot hand by assembling the fingers and a thumb. Fig. 11 shows the detailed design of the five-fingered robot hand.

4. Conclusions

We have developed a robot finger with four DOF, and confirmed its usefulness by experiments as the first step of the development of a robot hand. First, a novel driving method and a novel driving mechanism is designed. The driving method using ultrasonic motor and elastic element enables the five-fingered robot hand to conduct stable and soft grasping motion that needs no power supply. Moreover, the driving mechanism brings the robot finger the motion with equal number of DOF to human finger. Next, a robot finger with the driving method and the driving mechanism is implemented. The usefulness of the novel driving mechanism is confirmed by experiments. Further studies such as force control test and grasping test will be performed to confirm the effectiveness of the driving method. In addition, the elastic element will be optimized in order to maximize the controllability including response time. We are planning to develop a five-fingered robot hand by assembling the fingers and a thumb. The robot hand is expected to have soft and independent structure, and innovative performance.

Acknowledgement

This study was supported in-part by a Grant-in-Aid from Frontier Research from Keio Leading-edge Laboratory of Science and Technology.

References

[1] Kazuo Tanie: Design of Robot Hands, Industrial Robotics, Ed, S. Y. Nof, John Wiley & Sons, pp.112-137, (1982)

[2] Toshio Morita, Hiroyasu Iwata, Shigeki sugano: Human Symbiotic Robot Design based on Division and Unification of Functional Requiements, Proceedings of the 2000 IEEE International Conference on Robotics and Automation, pp.2229-2234, (2000)

[3] J. Butterfass, M. Grebenstein, H. Lieu, G. Hirzinger: DLR-Hand II: Next Generation of a Dextrous Robot Hand, Proceedings of the 2001 IEEE International Conference on Robotics and Automation, pp.109-114, (2001)

[4] S.C. Jacobsen, E.K. Iversen, D.F. Knutti, R.T. Johnson and K.B. Biggers : Design of the Utah/MIT Dexterous Hand, Proceedings of the 1986 IEEE International Conference on Robotics and Automation, pp. 1520-1532, (1986)

[5] C.S. Lovchic, M.A. Diftler: The Robonaut Hand : A Dexterous Robot Hand for Space, Proceedings of the 1999 IEEE Int. Conference on Robotics and Automation, pp. 907-912, (1999)

[6] http://www.shadow.org.uk/products/newhand.shtml

[7] J.K. Salisbury, M.T. Mason: Robot Hands and the Mechanics of Manipulation, MIT Press, Cambridge, MA, (1985)

[8] Bio-Industrial technology laboratory: Human Body Dimensions Data for Ergonomic Design, Human life technology research center, (1996) (in Japanese)