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Development of a Grounded Haptic Device and a 5-Fingered Robot Hand for Dexterous Teleoperation

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Abstract

In this paper, a grounded haptic device and 5-fingered robot hand are proposed. The grounded haptic device is developed to solve problems, such as complexity and tiredness of existing devices. We applied anatomical knowledge and neurophysiology to develop the novel haptic device. This device utilizes error of sense between visual and somatic sensation to simplify the mechanism. We also developed a 20 DOF robot hand for the slave device which is driven by ultrasonic motors (USMs), motors advantageous for a built-in mechanism applicable, and elastic elements. Elastic elements allow each joint to exhibit passive compliance, and force control without force sensors becomes possible. Both haptic device and robot hand have versatility. To evaluate these devices, we constructed a master-slave system. Even though the structures of the two devices are different the effectiveness, the system is shown through implementation.

1. Introduction

Recently, people concern about robots in order to progress in robotics. Above all, master-slave system draws attention as a new method to solve problems such as complexity and tiredness. Master-slave system is a teleoperation system in which a robot (slave) precisely reproduces work commanded by the operator through a device (master) manipulated by human. This system allows the robot to practice complicated tasks. For example, the system can be applied for telesurgery between USA and Japan or micro scale surgery that is difficult for humans to operate. This system is also to work in extreme situations such as operation in outer space and within nuclear reactors. A master hand is the input device to convey the position information to the slave hand. Usually, master-slave systems are operated by bilateral control. Bilateral control is a type of master-slave system control method.

When an operator manipulates the master device, position information is sent to the slave device. In turn, the slave device feeds back force information to the master device. The haptic device displays the fed back force to the operator to manipulate the slave robot efficiently. Therefore, haptic devices are usually applied to the master hand. Many researches have been conducted on haptic devices [1]～[6]. Previously developed haptic devices can be divided into two types: the wearable type and the grounded type. Both types have merits and demerits as shown in Table 1. Generally speaking, wearable haptic device has a exoskeleton mechanism. CyberGrasp is an example of a wearable haptic device [1]. It has an exoskeleton mechanism attached to the back of the hand so that it can easily measure the angles of each joint, and the structure design of this type is considered easier when interference with other fingers is taken into account. The Rutgers Master Ⅱ-ND is also an exoskeleton type placed on the palm side of the hand [2]. The structural interference restricts the movable range of the device. Usually, wearable type haptic devices are similar in structure to the human hand, which helps the operator to feel comfortable when manipulating them. The large

Table 1 Merits and demerits of the two types of haptic devices

	Wearable Type	Grounded Type
Merits	• Large Workspace • Easy to manipulate	• Compensation of device weight • Enable to sense weight of object
Demerits	• Impossible to display weight of object • Feel weight of device itself	• Limited workspace • Hard to be skilled

workspace wearable devices provide is another advantage. However, it has its weaknesses. Although it is impossible to display the weight of the object being handled, the operator has burden the weight of the device itself during an operation. Moreover, procedures to put them on are too complicated; therefore it is hard for the people with little experience to wear them.

On the other hand, grounded type haptic devices such as PHANToM [3] and SPIDAR [4] have structures that can compensate for its own weight, thus display the weight of objects. However, workspace becomes limited.

In the mean time, we have developed a 5-fingered robot hand as shown in Fig. 2. As for the slave device, a variety of robot hands have in the past been developed [7]〜[11]. Robot hands can also be divided into 2 categories according to its actuator arrangement. One is the external actuator type and the other is the built-in actuator type. The external actuator type helps simplify the structure of the device because the driving mechanism is composed of wires and actuators. However, this type is difficult to connect to robot arms in order to its structure. Moreover, Wire-driven mechanisms limit the movable range of fingers. The Utah/M.I.T hand [7], Robonaut hand [8], and shadow hand [9] are classified in this category. On the contrary, the built-in actuator type can realize dexterous manipulation and are versatile for connecting with robot arms. These robot hands have been actuated by DC motors or AC motors with reduction gear-heads to produce large torque. However, miniaturization of the robot hand size becomes limited and is dependent on the size of the actuator. DLR II [10] and WENDY [11] are examples of the built-in actuator type.

In our study, a new haptic device and a 5-fingered robot hand are developed. The haptic device has a unique concept and structure described in detail in the following section. It is a grounded 4-fingered device. This device can solve some problems such as described before. The robot hand is driven by ultrasonic motors and elastic elements. Owing to the

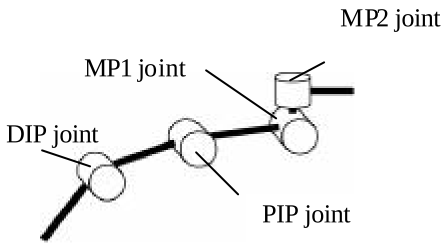

Figure 3 Arrangement of DOF

outstanding characteristics of ultrasonic motors, this hand is extremely small, the same in size as an average adult human hand, even though it is a built-in actuator type.

This paper is divided into 3 parts. First, the developed haptic device is mentioned. The design policy, structure design and features of the developed haptic device are mentioned. Next, the developed 5-fingered robot hand is described. Finally, the constructed master-slave system is introduced.

2. Development of Haptic Device

A. Design Strategy

The haptic device was designed based on 4 design concepts. First, the number of fingers was determined to be 4: thumb, index finger, middle finger and ring finger. This number is considered the minimum to execute stable grasping and manipulation. This haptic device constructs the master-slave system with 5-fingered robot hand. This haptic device constructs the master-slave system with 5-fingered robot hand. The input command from the ring finger of master device enables both of the ring finger and the little finger of the slave hand to move. Therefore, the little finger moves dependently with the ring finger. Secondly, the structural design policy is to be user-friendly and simple. The proposed device can compensate for its own weight because it is grounded. Thirdly, each finger has 3 DOF. Fig. 3 shows the arrangement of DOF of a

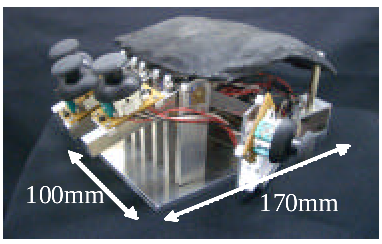

Figure 1 Developed haptic device

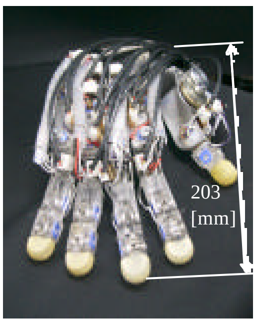

Figure 2 Developed robot hand

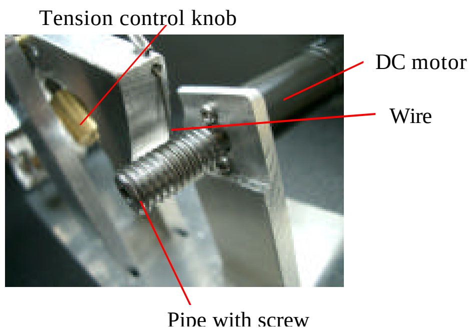

Figure 4 Compact wire mechanism

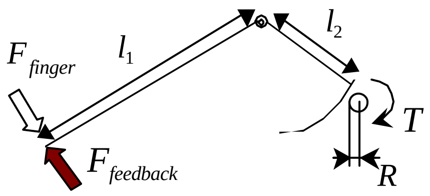

Figure 5 Model of force feedback

finger. Humans have 4 DOF for each fingers and the joints are called DIP, PIP, MP from the fingertip. In the proposed device, the DIP joint is dependent to the PIP joint because these joints are moved by same ligament of the finger. Moreover, the movable range of the device is limited by the hardware. Human's sensory illusion is applied for this device. Visual perception is known to have superiority over other sensory information, as is significant when moving a mouse pointer; humans can integrate visual and haptic information easily. Therefore, it will prove not to be much of a disadvantage with the movable range of the master hand being smaller than that of the slave. Finally, feedback force is displayed in 1 DOF for each finger. This feedback force displays counter force of grasping.

B. Driving Mechanism

Existing haptic devices are driven by various kinds of mechanisms. Link mechanisms have been applied in many cases. Since it is able to elevate stiffness easily by changing the material of the link, link mechanism enables slight delay drive train. Link mechanism can be divided into two categories. One is serial link and the other is parallel link. Serial link mechanism is mainly used for industrial manipulators. It is structurally simple as same as human finger and the workspace is larger than that of parallel one. On the other hand, serial link mechanism can not avoid the error accumulation and it is very hard to have actuators and sensors built-in links taken into consideration the design policy: device places inside the hand. Parallel link mechanism is applied to move end-effecter in parallel. Moreover, parallel link mechanism enables to set up actuators near the supporting point. On the contrary, parallel link mechanism occupies large space as contrasted its movable range. So, this does not satisfy the design policy. Next, cylinder mechanism is also applied for many machines. It is actuated by oil pressure or air pressure, so this mechanism can supply big force related to its cylinder's size. However, it is very hard to control its speed and torque. This problem can be solved by using a pressure sensor and a ball screw, big device is needed and the system becomes more complicated. Then, a belt mechanism is also popular mechanism to convey motive energy. Timing belt has higher stiffness than flat belt and wire. Friction loss is small enough: initial tension is 100N, friction torque is only 0.03Nm. Usually, distance between two axes is long for belt driven mechanism, so to solve this problem, idler or larger pulleys that have much more teeth is often applied. However, there are still a few backlashes and the structure must become big. Next, wire driven mechanism is used for many complicated small robots. Wire mechanism is categorized in two groups. First one is that wire displays the feedback force by using guide pulleys from actuator settled around operator's wrist or the back side of his hand. This mechanism enables actuators to be set anywhere you want. So mechanism becomes simpler than others. However, the delay occurs in order to its structure and friction loss is not negligible. Moreover, stiffness decreases by stretching wire because the slip between pulleys and wire happens so drive train efficiency is low. The other is that actuators move themselves by using drums and screwed motor axis. PHANToM applied this mechanism. This mechanism enables driving mechanism simpler and no backlash because there is no need for reduction gear.

On the proposed device, arranged compact wire mechanism is applied. Fig. 4 shows its structure. Proposed haptic device displays feedback force using DC motors as actuators. DC motor is easy to control, but DC motor has high speed and low torque. To solve this problem, DC motors are used with gear head. However, haptic device must have high back drivability to manipulate it naturally. To solve this problem, a

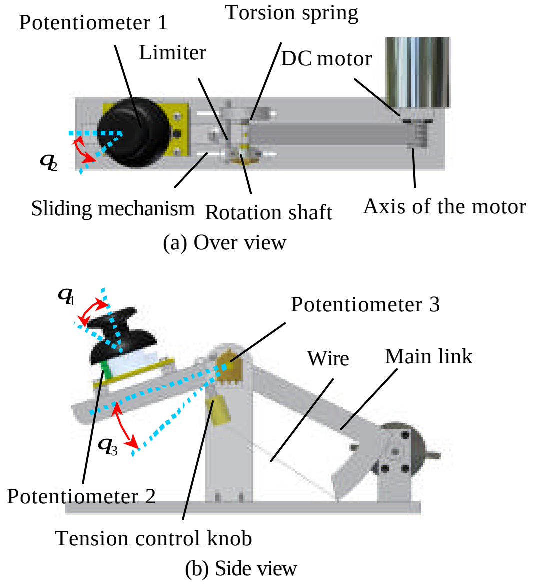

Figure 6 Outline of structure design

compact wire mechanism is applied for the power train. The tensioned wire is whipped around the screw connected with the motor shaft. This mechanism has following advantages.

(1) Compact and simple structure
(2) No backlash
(3) High back drivability

In case of this device, it is feedback force can be calculated easily. Fig. 5 indicates a model of force feedback. Displayed feedback force $F_{feedback}$ is described in following formula.

$$F_{feedback} = T \cdot \frac{l_2}{R} \cdot \frac{1}{l_1} \qquad (2.1)$$

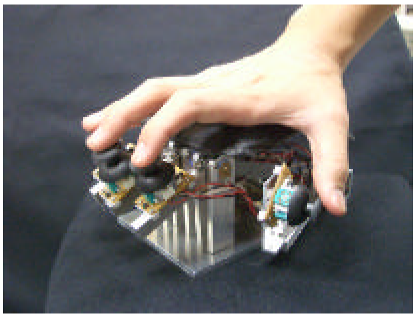

Figure 7 Developed haptic device

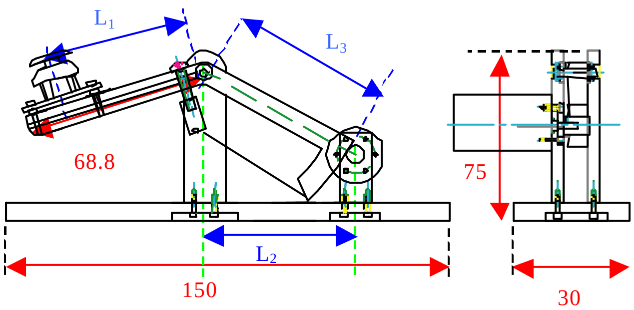

Figure 8 Detail design [mm]

Table 2 Detail dimensions [mm]

	L_1	L_2	L_3
index finger	40.2	70	75.3
middle finger	49.8	47.7	49.0
ring finger	42.2	23.8	38.1

Table 3 Movable range of device [deg]

	q_1	q_2	q_3
Movable range of device	−30〜30	−30〜30	0〜20

DC motors are chosen by this formula. Feedback force is set 5N for each finger. Therefore, maxon A-max 26 s applied for the actuator.

C. Structure Design

Fig. 6 shows you the outline of the index finger model. The device has 3 potentiometers to measure angular positions. There is a joystick covering two potentiometers on the fingertip to measure 2 axes of angular position. Potentiometer 1 is set to measure q_1, the movement of lateral fold of MP joint. Potentiometer 2 measures q_2, the movement of DIP joint and PIP joint. As I mentioned, these two joints move dependently, so the data from this potentiometer is used for two joints. Around the axis 1, there are a torsion spring and potentiometer 3 to measure q_3, hardware limiter and a fasten device. The torsion spring and the hardware limiter are built in the device to define initial position. Basically, 3 fingers of proposed device without thumb are constructed by this mechanism. The axis 1 of thumb is orthogonal to that of other fingers, so it is easy for operator to place his hand. Because of this, the axis 2 of thumb is also normal to the base. The base has slide mechanism to simplify assemble and tension changer.
To display feedback force, torque generated from the DC motor transmits as equation (2.1). Then operator feels the feedback force from slave hand. To attain more accurate and efficient operation, fingerstalls and the device cover need to be developed. The cover is necessary for relaxed position as shown in Fig. 7. This cover also restricts the movable range of fingers. The purpose for developing fingerstalls is solving following problems: present fingertips are slippery and the plane of finger does not run parallel with the plane of joystick.

D. Specification of haptic device

In this chapter, the feature of developed device is shown you. Table 2 indicates the feature of it. Fig. 8. shows you the detail design of the device. L_1 is the distance between axis 1 and joystick. This length is determined by the length between PIP joint and a fingertip to trace natural movement. L_2 and L_3 are the distance between axis 1 and axis 2 are taken into consideration the motor interference. Movable range of the device is shown in Table 3. The movable range is same in all fingers. q_1, q_2, q_3 are shown in Fig. 6. Total weight of the device is 1156.4g. The movable range of the developed robot finger is shown in Table. 4.

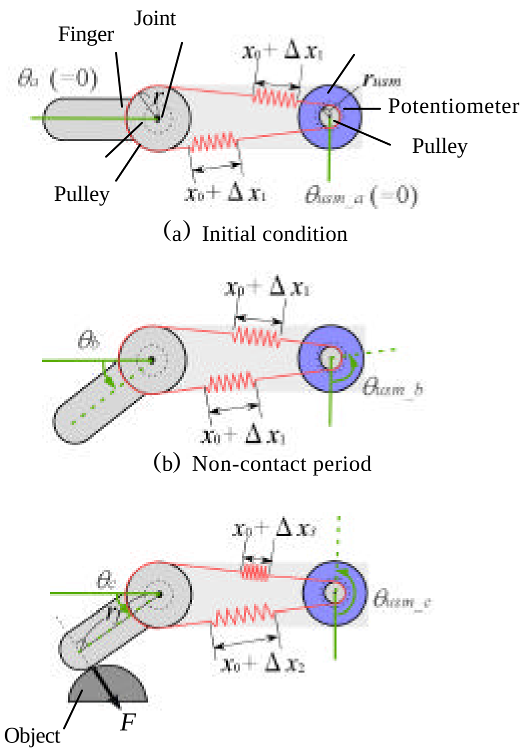

Figure 9 Outline of driving method

3. Development of a Five-Fingered Robot Hand

A. Driving Method

We developed a new driving method as shown in Fig. 9. 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

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).

$$r \cdot q_b = r_{usm} \cdot q_{usm\_b} \tag{3.1}$$

Then, when the finger gets in contact with any object, the equation (5.1) is not valid because the elastic elements deform. the contact period (c), the output force F caused by the during 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.

$$F \cdot r_f = 2 \cdot k \cdot (r_{usm} \cdot q_{usm\_c} - r \cdot q_c) \cdot r \tag{3.2}$$

In this equation, r_f represents the length of moment arm that is assumed to be definite. By the equation (5.2), the value of the contact force F is calculated by measuring two angular positions, q and q_{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 takes 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.

B. Driving Mechanism

Next, we introduce the driving mechanism of robot finger. The human finger has 3 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 4 DOF.

In order to imitate this structure, we decide the basic arrangement of DOF and joint names of robot

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finger as shown in Fig. 3. Then, on the premise that we use ring type ultrasonic motor, we design the driving mechanism as shown in Fig. 10. 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 motors 1-4 generate the motion of MP1, PIP, DIP and MP2 joint, respectively. The rotational angular positions of 4 joints and 4 motors are measured by eight potentiometers respectively.

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, the driving torque does not affect other joints. When the MP1 joint is driven by the ultrasonic motor 1, the relationship between Δq_{MP1} and Δq_{PIP} is given by the following equation because the wire between MP1 and PIP joints works like parallel link provided that $r_a = r_b$.

$$\Delta q_{PIP} = -\Delta q_{MP1} \quad (3.3)$$

At the same time, the relationship between Δq_{MP1} and Δq_{DIP} is given by the following equation.

$$r_d \cdot \Delta q_{DIP} = (r_e - r_c) \cdot \Delta q_{MP1} \quad (3.4)$$

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 Δq_{PIP} and Δq_{DIP} is given by the following equation because the wire is strained across.

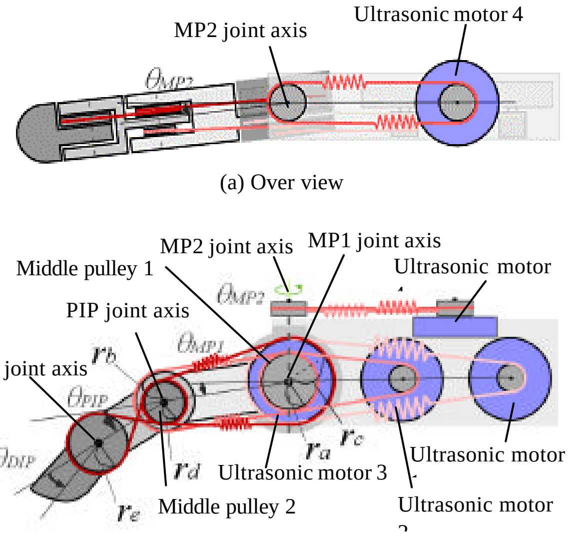
$$r_e \cdot \Delta q_{DIP} = r_d \cdot \Delta q_{PIP} \quad (3.5)$$

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 (3.5) 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 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 In addition, adduction-abduction motion is generated by ultrasonic motor 4 using the driving method described in section III A. The motor drives the whole finger part together with ultrasonic motor 3 as shown is Fig. 10 (a). Because the base plate with ultrasonic motors 1, 2 and 4 are fixed, there is little structural interference with fingers next to it.

Table 4 Movable range of each joints of the robot hand

Joint	Movable range [deg]
DIP joint	0～90
PIP joint	0～100
MP1 joint	−30～80
MP2 joint	−10～30



(a) Over view

(b) Side view

Figure 10 Outline of driving mechanism

4. Master-Slave System

We construct the master-slave system using developed haptic device hand and the robot hand. The outline of the control system is shown in Fig. 11. In this paper, 1-finger master-slave system is constructed. The angular position from the master hand is amplified and transmitted to the slave hand through a control PC. The slave hand reproduces the movement of the master hand and sends the force information to the master hand. After that, feedback force is displayed by DC motors.

5. Implementation

To evaluate the master-slave system, we carry out position control experiment. Fig. 12. shows you the tracking error of the system. In the experiment, potentiometer 1 and potentiometer 2 on master hand are used for evaluation. In Fig. 12. M indicates the angular position of the master hand and S indicates that of the slave hand. From this experiment, the effectiveness of

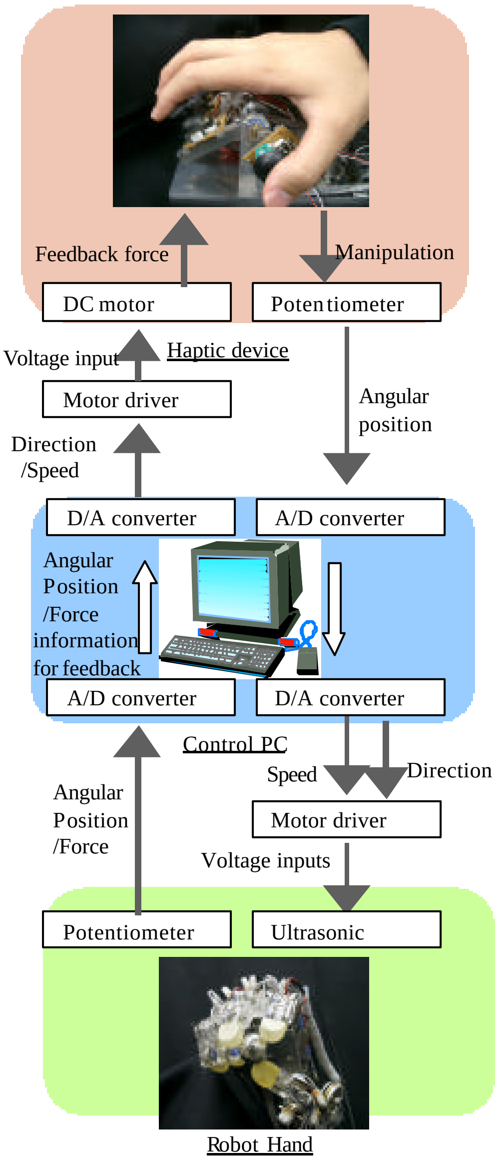


Figure 11 Outline of the control system

developed haptic device is shown you. An operator can use it easily.

6. Conclusion

We developed 4-fingered haptic device as a master hand to construct the master-slave system. This device is driven by DC motor and a compact wire mechanism. Movable range of the master device is smaller than the slave hand, so the displacement is amplified. The number of DOF is also lower than that of slave hand.

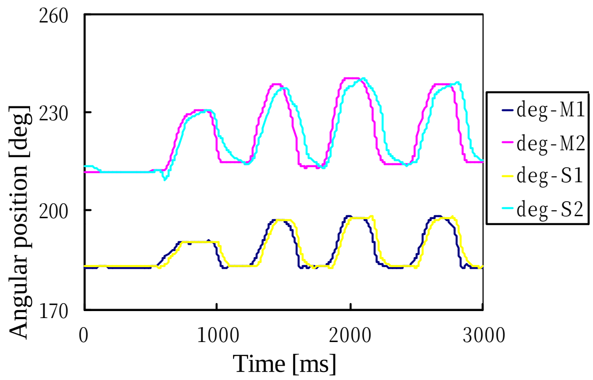


Figure 12 Result of position control

Therefore, we reduce DOF in line with the principle of subsidiarity between DIP joint and PIP joint. From the experiment, it is said that developed device is a user-friendly human-machine interface. Here are the problems to be solved: development of fingerstalls and a device cover, deployment to the 5-finger model.

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