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Development of a Mouse-Shaped Haptic Device with Multiple Finger Inputs

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***Abstract*— In this paper, a mouse-shaped haptic device is proposed. The device solves conventional problems of previously developed devices such as structure and control complexity and operating difficulties. We adopted multiple finger inputs in order to carry out complicated tasks and in order to highly adapt to the environment. To develop the multi-fingered haptic device, we focused on anatomical knowledge and neurophysiology. Since there is a primacy of the visual information over somatic sensation, we believe the movable range of human fingers does not necessarily have to be completely satisfied, i.e. visual information can compensate for the difference between the displacement of the haptic device and that of the slave device in a mater-slave system. We applied this feature to miniaturize and simplify the device. To confirm the usefulness of our developed device for a virtual reality system, we carried out three experiments: position control, familiarization and force feedback. The results show the effectiveness of the developed haptic device.**

Keywords- Haptic Interfaces; Teleoperation; Virtual Reality

I. INTRODUCTION

Recently, haptic devices are being extensively studied. Haptic devices are expected for two types of systems: virtual reality (VR) systems and master-slave systems. Virtual reality systems are expected for use in surgical simulations and for various training applications. On the other hand, master-slave systems are applied for tasks that are difficult for human to execute, such as dexterous micro operation and operation in extreme environments: cosmic space, inside nuclear reactors, etc. Haptic devices can measure movement of the operator, and thus display force feedback. Today, haptic devices with multiple finger inputs are attracting attention because multi-fingered manipulation helps realize complicated operation and is highly adaptable to the surrounding environment. During the last decade, several haptic devices with multiple finger inputs were developed [1]-[6]. These devices can be divided into two categories: the grounded type and the exoskeleton type. Grounded haptic devices mainly measure a point using instruments such as a pen and a ball. The operator can feel feedback force from wall and the weight of grasping object. Furthermore, the weight of the device can be compensated. Therefore, the operator can manipulate the device with ease. However, there lies a fundamental problem in which the workspace becomes limited since the device is grounded. Thus, the movable range of the fingers narrows as the number of finger inputs increases and restricts the operator from conducting natural movement. Therefore, it is difficult to develop devices with multiple finger inputs. As a result, the structure of the device becomes large and control of the system becomes complicated.

On the other hand, the exoskeleton type haptic devices are mainly shaped like a glove to fit into back of the hand. Since the shape of the device is very much like a hand, operator can manipulate it intuitively. This type is more suitable for multiple finger inputs and has a larger workspace compared to the grounded type because the structure is on the operator's back of the hand. However, it is difficult for existing exoskeleton type haptic devices to display multi degree of freedom (DOF) force feedback due to their structure. Furthermore, the operator has to bear the weight of the device and the device cannot display the weight of a grasping object or feedback force from a wall when in contact. Furthermore, there is something wrong with wearing the device. Thus, it is difficult for the operator to manipulate objects naturally.

As shown above, both types have problems. To solve these problems, it is necessary to develop a new type of haptic device with the following characteristics:

(1) Simple and compact structure
(2) Usability
(3) Comfort

The purpose of this paper is to introduce a new haptic device which satisfies these features and to show its effectiveness by several experiments.

The design and fabrication of the device are introduced in Section II. The characteristics of the device are discussed in Section III. Next, evaluation using a VR system is described in Section IV. Next, discussion and future works are presented in Section V, and finally conclusions of this study are presented in Section VI.

II. DESIGN AND FABRICATION OF THE DEVICE

A. Basic design

In this section, the basic design of the haptic device is introduced. To satisfy the characteristics described in Section I, we focused on human features; from anatomical and neurophysiological viewpoints. Anatomically, humans are said to have a certain functional position [7], which is a most appropriate position for the human hand to grasp or manipulate as shown in Figure 1. The proposed device takes an idealized mouse-like form in order to operate the device maintaining this functional position. The names of the joints are also shown in Figure 1. The four fingers other than the thumb have similar structures that consist of an MP joint, PIP joint and DIP joint. The DIP joint moves simultaneously with the PIP joint. This relationship has been approximated as shown in (1)[5]. We adopted this feature to simplify the mechanism of the device. With the thumb, the MP joint works with the IP joint in addition to the relationship between the PIP and DIP joints [8] as shown in (2).

$$\theta_{DIP} = 0.46 \cdot \theta_{PIP} + 0.083 \cdot \theta_{PIP}^{\ 2} \qquad (1)$$

$$\theta_{MP} = 1.1341 \cdot \theta_{IP} + 0.286 \cdot \theta_{IP}^{\ 2} \qquad (2)$$

With the object of neurophysiology, there is a primacy of visual information over somatic sensation. Therefore, as long as the operator is given visual information of the workspace, the movable range of the device may be reduced. We took advantage of this phenomenon to simplify and miniaturize the structure of the device. In addition, since there is no need to satisfy all the movable range of fingers, the proposed device can improve manipulation performance.

From these design concepts, the basic design is as follows:

First, the device requires 4 fingers to execute stable grasping and manipulation [9]. Next, each finger has 3 degrees of freedom (DOF). Although human fingers have 4 DOF, we reduced the DOF owing to the relationship between the DIP and PIP joints for the 3 fingers other than the thumb, the MP and IP joints for the thumb as shown in equations (1) and (2). Figure 2 shows the structure design of an one-finger model. Potentiometer 1 measures the flexion movement of MP joint, shown in the diagram as θ_1. Adduction-abduction movement of the MP joint and movement of the PIP and DIP joints are measured by potentiometers 2 and 3 respectively (θ_2, θ_3). A joystick and rotation shaft measures three DOF movements. Feedback force is displayed against the palmer surface of fingers because it is the most important part for grasping and manipulation. This structure also has a counter weight through the rotation shaft. Since the weight of the device is compensated, this mechanism enables the operator to manipulate the device naturally.

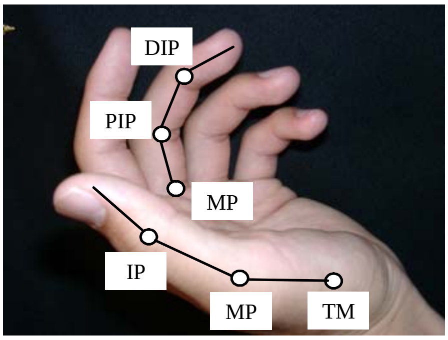
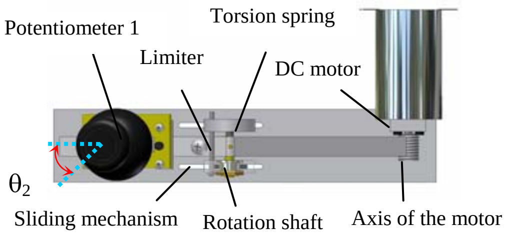
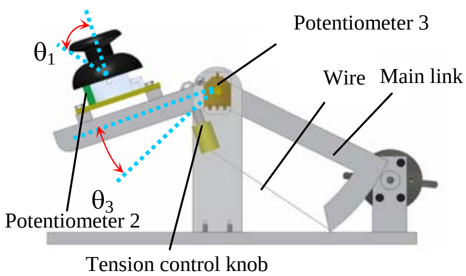


Figure 1. The functional position and the names of joints



(a) Over view



(b) Side view

Figure 2. Outline of structure design

B. *Driving mechanism*

Force feedback mechanisms can be divided into two categories: passive force feedback [10]-[12] and active force feedback [1]-[6]. Brakes and crutches, ER fluid are mainly applied for the passive type. In this category, actuators do not move until operators manipulate the master device, thus it is safe. Then, it is possible to display a large force feedback without danger. However, force patterns that can be displayed are limited because force feedback is displayed only passively. On the other hand, the active type displays force feedback by controlling actuators. Especially, to continuously display variable force feedback, this method can be considered superior to the passive type. It is also said that the active type is dangerous because actuators may move independently regardless of the operator's intentions. However, feedback force is not very large and the movable range of the device is small. Hence these problems are negligible. Therefore, the active type mechanism is applied to the proposed device.

DC motors are used as actuators in the proposed device. DC motors have two characteristics: control simplicity, ability to display force feedback actively. The Current/Torque property of DC motors has a linear relationship. Thus, controlling feedback force is easy. However, DC motors are also known for high rotation speed and low torque. Therefore, DC motors are used with gear heads when implementing to a haptic device. Haptic devices are then manipulated by human actively. Thus the mechanism should be back drivable. Putting together these factors listed above, the driving mechanism should have the following characteristics:

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

Therefore, a compact capstan mechanism is proposed as shown in Figure 3. A tensioned wire is wrapped around a screw connected to the motor shaft. Reduction gears are not used in this mechanism, thus there is no backlash.

Moreover, this mechanism has high back drivability

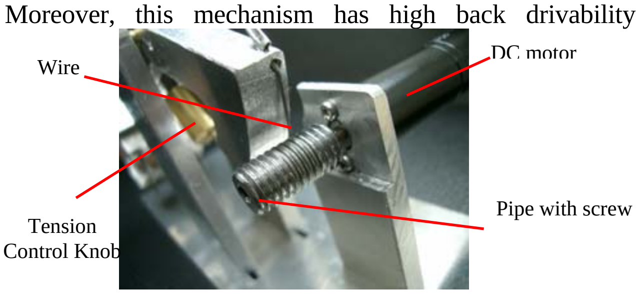


Figure 3. Compact wire mechanism

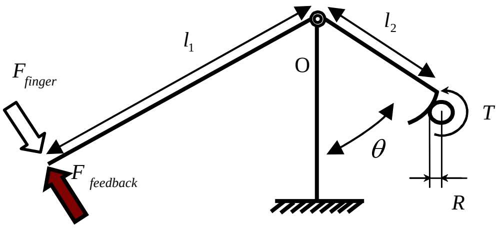


Figure 4. Model of displaying force feedback

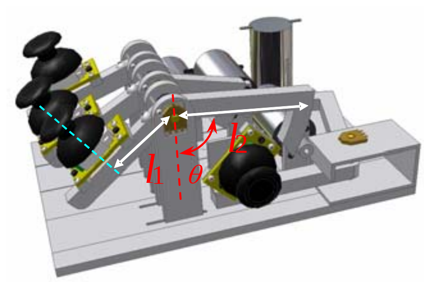


Figure 5. Detailed design of the haptic device

TABLE I. DIMENSION OF THE DEVICE

	l_1 [mm]	l_2 [mm]	θ [deg]
Index finger	40.2	75.3	62
Middle finger	49.8	49.0	64
Ring finger	42.1	38.1	34
Thumb	64.5	87.8	86

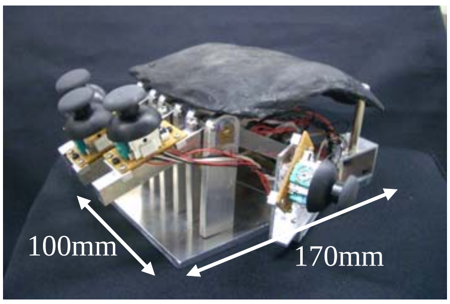


Figure 6. Developed haptic device

because reduction gears are not required. To manipulate naturally, reaction force must be as small as possible. A rotation link is used to transmit force quickly. It is able to elevate stiffness can be elevated by changing the material of the link.

In this device, the feedback force can be calculated easily. Figure 4 shows the relationship between external force and motor torque. Displayed feedback force is derived by the following formula.

$$F_{feedback} = T \cdot \frac{l_2}{R} \cdot \frac{1}{l_1} \qquad (3)$$

DC motors are chosen from this formula. Feedback force is set at 5N for each finger to carry out precise grasping. Therefore, a maxon A-max 26 motor is selected as the actuator for each finger. Motor drivers (TITech DRIVER JW-0143-2) are used to control the current to drive the motors.

C. Detailed design

In this section, the detailed design of the multi-fingered device is presented. Figure 5 shows the detailed design of the proposed device consisting of four fingers. Structures of the three fingers other than the thumb are almost the same, and are distributed parallel to each other. The axis of the rotation shaft of the thumb is perpendicular to the other three fingers to fulfill the usage in the functional position. l_1 and l_2, θ are different for each finger as shown in Table 1. l_1 is determined referring to the length from the PIP joint to the fingertip. l_2 and θ are fixed to avoid interferences among motors, the main links, the base and pillars. The movable range of the main links is also taken into account. The length l_2 of the index finger is longest among the three parallel fingers. Because it is to say that index finger has the strongest power among the three fingers. Equation (3) indicates that l_2 is related to the feedback force. Figure 6 shows the developed haptic device. The structure is basically the same as the detailed design as shown in Figure 5, only the developed device has the cover. This cover is placed to support the weight of the operator's hand, and is made of free plastic to fit the configuration of the palm. In addition, the movable range of the operator's finger is limited naturally by this cover.

III. CHARACTERISTICS OF THE DEVICE

In this section, the characteristics of the mouse-shaped haptic device are described. First, the movable range of the device is described. Secondly, accuracy in determining the position and displaying the feedback force are mentioned.

TABLE II. MOVABLE RANGE OF THE DEVICE [DEG]

θ_1	θ_2	θ_3
-30～30	-30～30	0～20

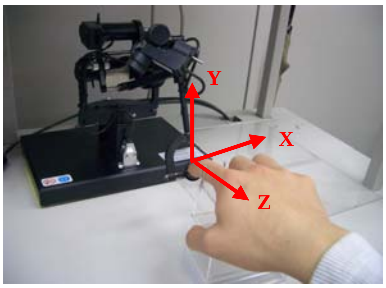


Figure 7. Measurement of the movable range of fingers

Thirdly, comparisons with other haptic devices are discussed.

A. Movable range of the device

As is mentioned above, the developed device does not satisfy all the movable range of human fingers completely while previously developed devices have attempted to do so. Table 2 shows the movable range of the device. θ_1, θ_2, θ_3 are mentioned in Table 2.

We compared the movable range of a human finger and operation point of the device using a haptic device, PHANToM, as shown in Figure 7. PHANToM is known for the accuracy in measuring 3 dimensional positions. Figure 8 indicates the comparison of movable range between human finger and fingertip of the device in the YZ plane. Displacements are converted into a dimensionless value. This figure shows that the movable range of the device does not satisfy that of human fingers. However, the values corresponded within the encircled area. This means that it is possible to move fingertip naturally within that area when operators manipulate the device.

B. Accuracy of position and force feedback

To evaluate the accuracy of determining position and displaying force feedback, we carried out two experiments.

First, to confirm a resolution of the developed device, we measured the position of the operation point using potentiometers and PHANToM. As mentioned above, PHANToM can measure accurate position (resolution: 0.02mm), thus we compared it with calculated position by solving kinematics. As a result of comparing five different positions, errors of determining position are following: the average error was 0.84mm and the maximum error was 1.34mm. These result can be reduced.

We next examined the accuracy of displayed feedback force. Force feedback of the haptic device is controlled by the motor driver. Therefore, calibration of the motor driver was done beforehand. In the experiment, the calculated feedback force from command voltage to the motor driver is compared to weights fixed to the operation point. The weight is 0.2kg each. The weight increased to 1.0kg. According to the result, all fingers were able to display force of more than 6N. 6N satisfies the fixed value (5N). The index finger could display 10N which was the largest force. Average error of the feedback force is 0.44N and 0.75N maximum which we consider small enough.

C. Comparison with other devices

Table 3 shows the comparison with other devices. PHANToM is selected as an example of grounded haptic devices and CyberGrasp for the exoskeleton type. While PHANToM is superior to other devices, it has only one operating point. To increase operation points, the number of PHANToM must be increased. It is thus very difficult to develop multiple finger inputs. The mass of CyberGrasp is 0.35kg. The operator has to bear this weight during manipulation. Furthermore, CyberGrasp can display feedback force in only one DOF (the flexion direction) for each finger even though it has a complicated mechanism. The developed device also displays one DOF of feedback force; however the driving mechanism makes it possible to display both flexion and extension. The developed haptic device has characteristics of both of the types, namely, the following:

(1) The device is grounded and is shaped like a mouse
(2) Simple structure and multiple inputs are consistent
(3) The operator can manipulate the device viscerally and weight of device is compensated

From these characteristics, it is found that the developed device fulfills the design concepts.

IV. Evaluation in VR System

We constructed a VR system as shown in Figure 9. The constructed VR system is composed of the developed haptic device, a virtual hand and a virtual object. OpenGL is applied to draw the VR space. In this section, the virtual hand model is first introduced. Next, experiments conducted on position control, usability and displaying force feedback are described.

A. Virtual hand model

To construct the VR system, the structure of the virtual hand has to be determined. In our case, virtual hand is constructed by imitating the human hand in order to carry out dexterous work and be highly adaptable to the

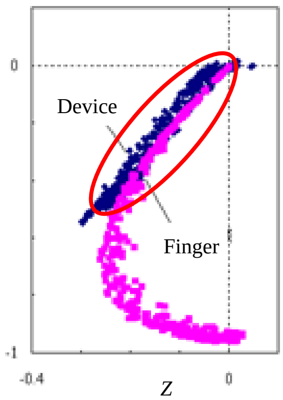


Figure 8. Comparison of movable range

TABLE III. Comparison with other devices

	PHANToM	CyberGlove/Grasp	The Developed Device
weight of operation poit	0.08kg	0.35kg	negligible
movable range	420×590×820mm	hemisphere (radius 1m)	radius 44mm (for each fingers)
resolution	0.02mm	0.5deg, 0.06mm	0.841mm
max feedback force	22N	12N	10N
DOF (position)	6	18(22)	12
DOF (force feedback)	3	5	1
renewal rate of measure posistion	1ms	9ms	2ms
renewal rate of displaying force	1ms	No Data	2ms

surrounding environment. The virtual hand has five fingers and each finger has four DOF. The human, thumb has 5 DOF anatomically. However, one DOF is negligible owing to the small movable range. In conventional master-slave systems, the fingertip position of the master is sent to the slave as command. However, since the fingertip position is unimportant in the developed device, angular positions of each joint is transmitted to the slave and expanded as mentioned in Section II, taking advantage of the priority of visual information to tactile information. Figure 10 shows the transformation of the angular position. Since the developed device has 3 DOF, it is necessary to transform the angular position of each joint. As previously described in Section II, θ_3 moves MP1 (TM1 for thumb), θ_1 moves PIP and DIP. θ_2 moves MP2. To move PIP and DIP together, (1) is applied. For the thumb, (2) is applied. From these angular positions, the position of fingertip can be calculated solving kinematics from (4)-(6).

$$x = \left(d_1 \cos(\theta_1) + d_2 \cos(\theta_1 + \theta_2) + d_3 \cos(\theta_1 + \theta_2 + \theta_3)\right) \cdot \sin(\theta_4) \quad (4)$$

$$y = \left(d_1 \cos(\theta_1) + d_2 \cos(\theta_1 + \theta_2) + d_3 \cos(\theta_1 + \theta_2 + \theta_3)\right) \cdot \cos\theta_4 \quad (5)$$

$$z = d_1 \sin(\theta_1) + d_2 \sin(\theta_1 + \theta_2) + d_3 \sin(\theta_1 + \theta_2 + \theta_3) \quad (6)$$

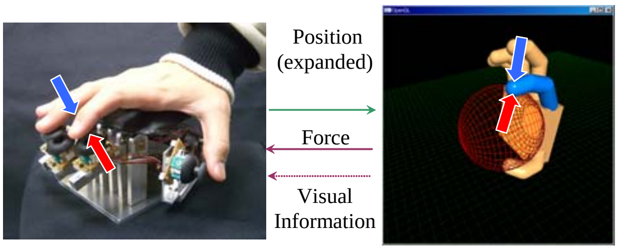


Figure 9. VR system of using the developed device

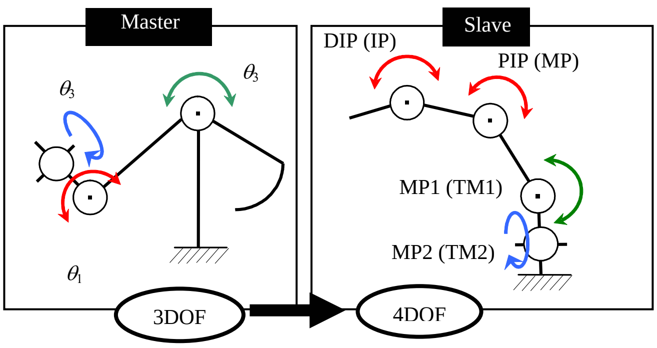


Figure 10. Transformation of angular position

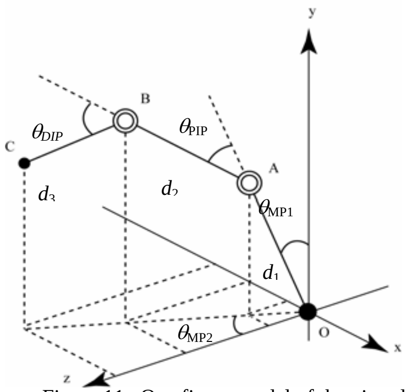


Figure 11. One finger model of the virtual hand

d_1, d_2, d_3 are length of the link as shown in Figure 11.

B. *Implementations*

To evaluate the efficiency of the developed device, we conducted three experiments.

First, an experiment on position control was performed. The finger of the developed device lacks one DOF compared to a human finger and the movable range of the device does not satisfy that of humans. In this experiment, we confirmed how many kinds of position could be controlled by the developed device. The results are shown in Figure 12. 12 different positions categorized as types of grasping. The upper side is power grasping and the lower one is precision grasping. Since these positions were controlled with ease, we believe the developed device can carry out dexterous manipulation.

Next, the experiment on usability was conducted. Since haptic devices are a human interface between the operator and VR space, usability is an important issue. In this experiment, we compared the time it took to control

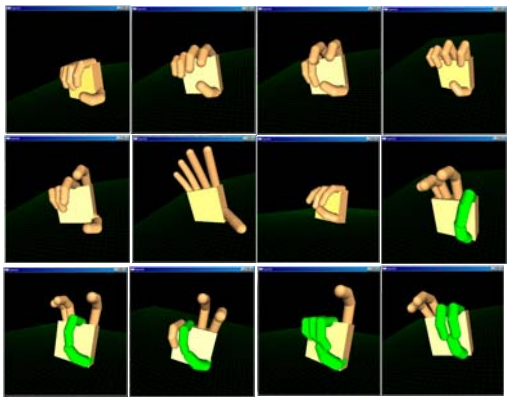


Figure12. Position control of virtual hand

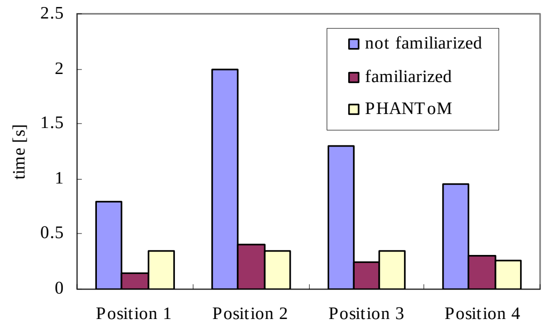


Figure 13. Result of familiarization test

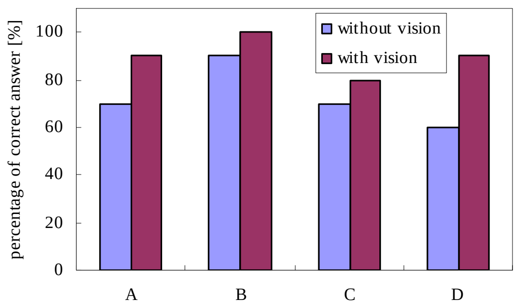


Figure14. Result of stiffness distinction test

position of virtual hand before and after familiarization. Position 1 is making a fist. Position 2 is that all fingers are fully extended. Position 3 is making the sign, "OK." Position 4 is making scissors. The time measured was also compared to PHANToM. PHANToM has 6 DOF, so if the time of the device is close to PHANToM, we can say the developed device is easy to manipulate. We measured the movement of index finger with the fixture indicated in Figure 2. Figure 13 shows the results. To become familiar with the device, the operator had to carry out position determination five times. Improvement could not be found after the sixth time. Before the familiarization, it took several seconds to determine the position. However, once familiar, the time improved to that of PHANToM. For position 1 and position 3, the time was shorter than PHANToM. From this result, the developed device can be considered easy to familiarize.

Finally, we carried out the evaluation test on displaying force feedback. A virtual object was used in this experiment. The virtual object is constructed to have an elastic property. Feedback force is displayed while the fingertip of the virtual hand is in contact with the virtual object. The feedback force is controlled to become larger when the fingertip moves further into object. In this experiment, two randomly selected virtual objects from five different types of stiffness are compared by four subjects with and without visual information. The results are shown in Figure 14. Without visual information, the percentage of an accurate answer was 72.5%. On the other hand, percentage was 90% with sight. Figure of 72.5% is high related to its simple mechanism and without sight. The accuracy is increase to 90 % with sight. From these results, we can say that the driving mechanism could display feedback force faithfully.

V. DISCUSSIONS AND FUTURE WORKS

In this paper, the developed mouse-shaped haptic device was described.

Feedback force can also be displayed in both the extension and flexion direction. The size of the human hand differs with each person. To begin with, it is found that the structure of the developed device is efficient, we make the device smaller. Since the validity of the structure has been confirmed in this study, miniaturization will be future work. Since the structure is simple, miniaturization should be easy.

The developed device can only measure the movement of the finger. We plan on developing a device which can also measure the movement of the hand. Additional DOF will be given to the base as shown in Figure 15. The developed device is expected to be applied to some kinds of field such as a master-slave system and surgical simulation using VR system.

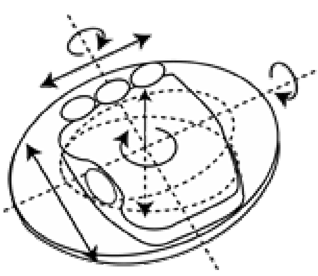


Figure 15. Future works

VI. CONCLUSION

In this paper, we developed a haptic device with multiple finger inputs for operation of remote and virtual multi-fingered dexterous robot hands. The priority of sight to haptics in sensing a displacement is applied upon designing the device. The efficiency of the device is confirmed through evaluation experiments. The developed device could carry out complicated tasks with the simple mechanism. Furthermore, it is easy to manipulate and it can be applied to a device which can measure whole movement of hand.

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