ICAT 2001
December 5-7, Tokyo, JAPAN

Evaluation of Two-Handed Multi-Finger Haptic Device SPIDAR-8

Yoshio KOHNO[1)], Somsak WALAIRACHT[1)], Shoichi HASEGAWA[1)], Yasuharu KOIKE[2)], and Makoto SATO[2)]

Precision and Intelligence Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, 226-8503 Japan
[1)]*{kohno,somsak,hase}@hi.pi.titech.ac.jp,* [2)]*{koike,msato}@pi.titech.ac.jp*

Abstract

This paper evaluates a two-handed multi-finger haptic device SPIDAR-8. The SPIDAR-8 has eight fingertip attachment devices in which each fingertip attachment device is connected with three strings. The SPIDAR-8 calculates a 3D position of each fingertip using the lengths of three strings connecting to that fingertip attachment device, and controls tensions of three strings to display a force feedback when the position of any finger comes into contact with the virtual object. It allows the user to manipulate the virtual objects in the computer simulated virtual environment with the sensation that the manipulated virtual objects are real. The experimental results of a Fit-The-Face task using SPIDAR-8 show effectiveness.

Key words: Haptic Device, SPIDAR, Virtual Reality

1. Introduction

To interact with the computer simulated virtual environment with the same sensation as in real world using the hands, we need an interface device that can input the motion of our hand and provide the sense of touch from the interaction. Such interface must make two-handed operation and multi-fingered operation, because some tasks require the cooperative works of two hands and more stable grasping of the object by multi-fingers.

Haptic interface devices are fastened to a desktop or to parts of the user's body. An example of the most popular desktop force feedback interface device is the PHANToM[1]. It is a weight-counterbalanced and back-drivable arm that has six degrees of freedom. The PHANToM is well suited for point interaction by a finger. Two-handed and multi-fingered manipulation needs at least four PHANToM arms.

Wearable haptic interface devices attach to the user's body allowing free movement and a larger workspace than in the desktop counterparts. The only commercialized haptic glove is the CyberGrasp[2]. The CyberGrasp uses a position sensing CyberGlove and a cable-driven exoskeleton structure attached on the back of the user's hand. The complex structure guides tendons transmitting forces to the hand produced by electrical motors in a remote placement control box. This results in high backlash and friction. Moreover, the glove is quite heavy; it can easily lead to user fatigue during prolonged use.

SPIDAR-8[3][4] has been developed in this laboratory as two-handed multi-finger haptic interface device. SPIDAR-8 has eight fingertip attachment devices in which each fingertip attachment device is connected with three strings. SPIDAR-8 calculates a 3D position of each fingertip from the length of three strings connecting to that fingertip attachment device, and controls the tensions of three strings to display the force feedback when the position of any finger comes into contact with the virtual object. It allows the user to manipulate the virtual objects in the computer simulated virtual environment with the sensation that the manipulated virtual objects are real. This paper evaluates Two-Handed Multi-Finger Haptic Device SPIDAR-8.

2. System Design and Construction

2.1. System Design

SPIDAR-8 is string-based haptic interface devices. If the actuators, that control strings, are attached to the user's hand or fingers, the device can be complex and heavy. If the actuators are placed remotely, the device can be simple and the user needs not to sustain weight of the device. Each actuator is placed on the frame that is large enough for the working space of both hands. The frame is 80cm in width, 60cm in height, and 60cm in depth. To be able to display force feedback on a finger in any direction in 3D space, 4 strings are necessary. But, if we attach 4 strings to each finger, there will be too many strings. It limits the movement of the user's hands and fingers. Therefore the number of strings is 3. Fig.1 shows the photograph of a pair of the actuator. There are 24 actuators attached on the frame as shown in Fig.2. The locations of each actuator with the corresponding sensing finger are summarized as shown in Table 1. Fig.3 shows that the user is wearing the caps on the fingertips.

2.2. System Construction

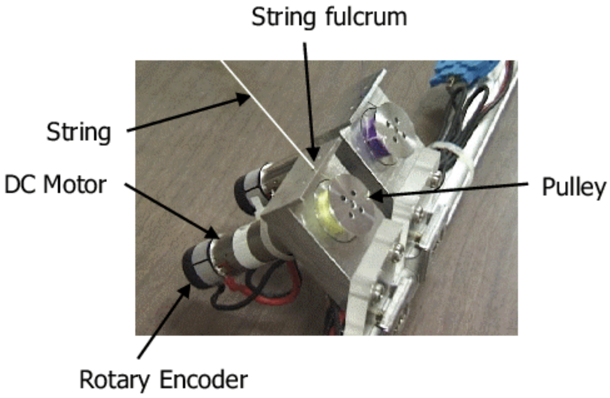

Fig. 1 Actuator

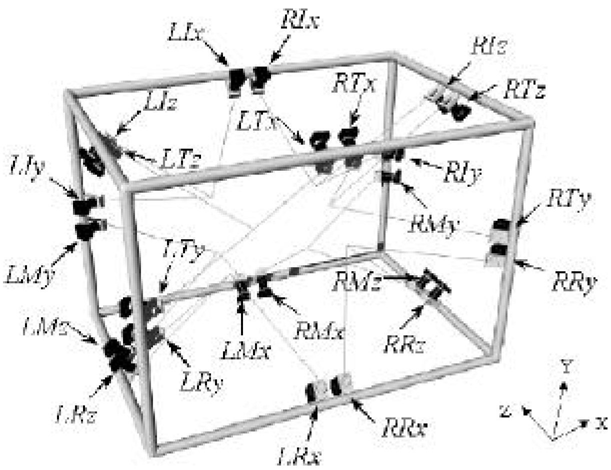

Fig. 2 Location of 24 actuators on the frame

Table 1 The actuators to the corresponding fingctip

Actuator	Sensing finger	Actuator	Sensing finger
(LT_x,LT_y,LT_z)	Left Thumb	(RT_x,RT_y,RT_z)	Right Thumb
(LI_x,LI_y,LI_z)	Left Index	(RI_x,RI_y,RI_z)	Right Index
(LM_x,LM_y,LM_z)	Left Middle	(RM_x,RM_y,RM_z)	Right Middle
(LR_x,LR_y,LR_z)	Left Ring	(RR_x,RR_y,RR_z)	Right Ring

System block diagram is shown in Fig.4. A personal computer is used for controlling the system. The up/down counter boards count the signal pulses read from each rotary encoder. The personal computer controls the amount of current through motor amplifier to each motor by the D/A converter boards.

3. Position Sensing and Force Feedback

3.1. Position Sensing

SPIDAR-8 senses each fingertip position on the user's hand using the length of three strings. To measure the length of each

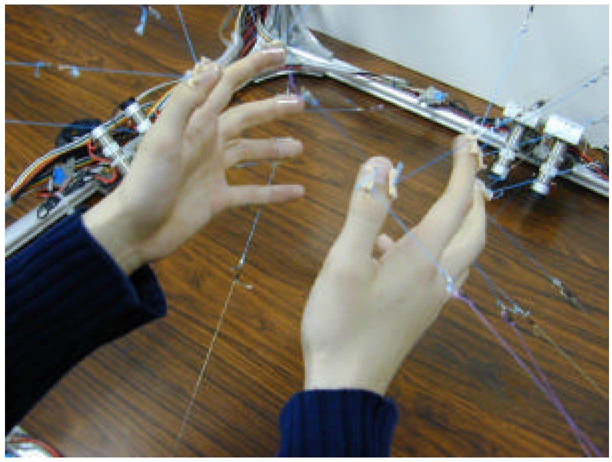

Fig. 3 Fingertips attachment

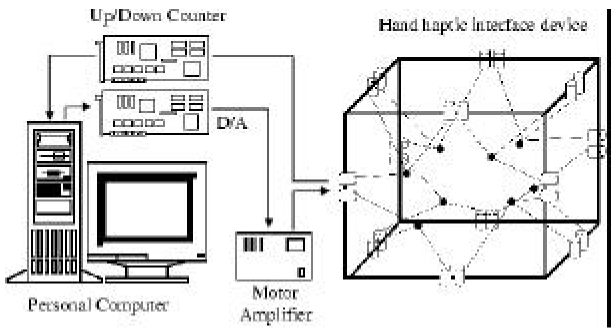

Fig. 4 System block diagram

string correctly, each motor is controlled to pull the string by small amount of force about 0.3N to straighten the string.

Let $l_i\,(i=1,2,3)$ be the length of each string measured from a fingertip position P to the corresponding string's fulcrum $A_i\,(i=1,2,3)$. The vectors $\overrightarrow{n_1}$ and $\overrightarrow{n_2}$ are unit vectors along the vectors $\overrightarrow{A_1A_2}$ and $\overrightarrow{A_1A_3}$, which are connecting between the string fulcrums A_1A_2 and A_1A_3 respectively. A vector $\overrightarrow{n_3}$ is the cross product of the vectors $\overrightarrow{n_1}$ and $\overrightarrow{n_2}$, which defines the position of P that always lies inside the space enclosed by the frame.

Considering the diagram shown in Fig.5, we have

$$\overrightarrow{n_1} = \frac{A_2 - A_1}{\|A_2 - A_1\|}$$

$$\overrightarrow{n_2} = \frac{A_3 - A_1}{\|A_3 - A_1\|}$$

$$\overrightarrow{n_3} = \overrightarrow{n_1} \times \overrightarrow{n_2}$$

and the position of point P can be calculated by the following equation:

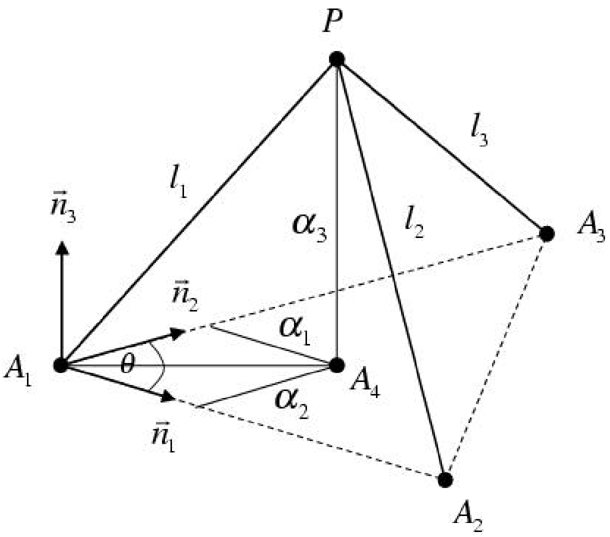

Fig. 5 Position measurement

$$P = A_1 + \alpha_1 \vec{n_1} + \alpha_2 \vec{n_2} + \alpha_3 \vec{n_3}, \qquad \alpha_3 \geq 0$$

where α_1 , α_2 and α_3 can be derived from the following equations:

$$\alpha_1 = \frac{1}{\sin^2 \theta} \left(\frac{K_1}{d_1} - \cos\theta \cdot \frac{K_2}{d_2} \right)$$

$$\alpha_2 = \frac{1}{\sin^2 \theta} \left(\frac{K_2}{d_2} - \cos\theta \cdot \frac{K_1}{d_1} \right)$$

$$\alpha_3 = \sqrt{l_1^2 + \left\| \alpha_1 \vec{n_1} + \alpha_2 \vec{n_2} \right\|^2}$$

$$\theta = \cos^{-1}\left(\vec{n_1} \cdot \vec{n_2} \right)$$

$$d_1 = \left\| A_2 - A_1 \right\|$$

$$d_2 = \left\| A_3 - A_1 \right\|$$

$$K_1 = \frac{1}{2}\left\{ d_1^2 - \left(l_2^2 - l_1^2 \right) \right\}$$

$$K_2 = \frac{1}{2}\left\{ d_2^2 - \left(l_3^2 - l_1^2 \right) \right\}$$

3.2. Force Feedback Generation by 3 Strings

To display force feedback at each fingertip of the user, SPIDAR-8 controls the amount of electric current entering each motor. The tension force on each string, $t_i (i = 1,2,3)$, and the unit vectors $\vec{u_i} (i = 1,2,3)$ are used to compose the resultant force vector as shown by the following equation:

$$\vec{f} = \sum_{i=1}^{3} t_i \vec{u_i}$$

where

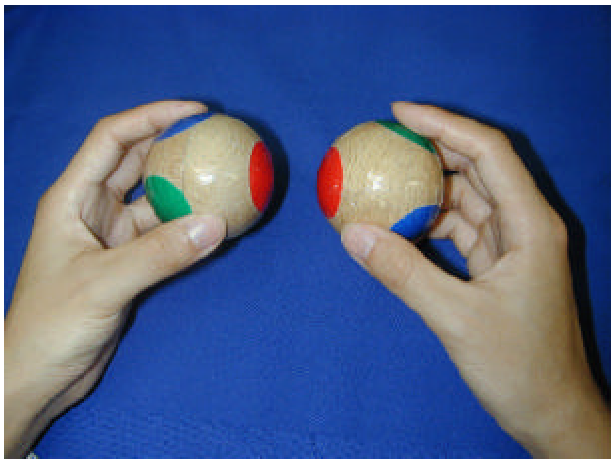

Fig. 6 Fit-The-Face task with real spheres

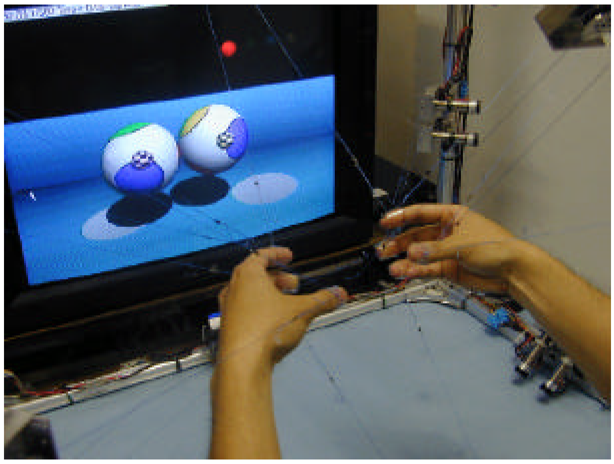

Fig. 7 Fit-The-Face task with virtual spheres using SPIDAR-8

$$\vec{u_i} = \frac{A_i - P}{\left\| A_i - P \right\|}$$

Three strings from three different fulcrums connected to a point for each finger form a triangular cone of possible force displayable to that finger. In fact, force feedback can only be correctly displayed if the resultant force vector lies inside this force cone. However, if the computed resultant force vector lies outside the force cone, the force vector is projected onto the force cone and the resultant force vector is recomposed. By this way, SPIDAR-8 can display force feedback in the appropriate direction and magnitude.

4. Evaluation

The ability of performing the two-handed objects manipulation task is evaluated. A kind of simple assembly task called Fit-The-Face is setup. The task is to grasp two spheres, one by each hand, and fitting 4 pairs in the same color of circular marker painted on the spheres. The experiment contains the trials performed with real spheres(Fig.6) and the virtual spheres performed by using SPIDAR-8(Fig.7). Fig.8 shows that the user is manipulating the virtual spheres with SPIDAR-8.

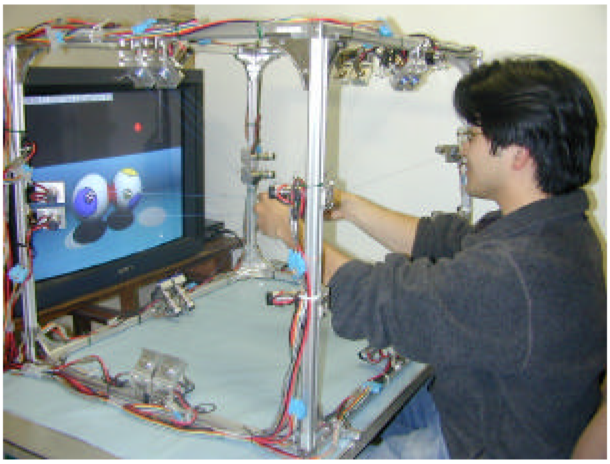

Fig. 8 Manipulation using SPIDAR-8

Table 2 Averages completion time resulted from Fit-The-Face task

No. of Finger	Object	Constraint	Average completion time (unit in second)				
			Subject				Overall
			A	B	C	D	
2	Real	w/o cap	5.11	4.45	6.24	4.60	5.10
		w. cap	13.92	15.22	19.59	15.42	16.04
	Virtual	w. force	18.81	15.96	26.85	27.55	22.29
		w/o force	22.47	19.38	24.45	28.18	23.62
3	Real	w/o cap	4.81	4.65	6.02	5.31	5.20
		w. cap	7.62	7.38	9.85	9.74	8.65
	Virtual	w. force	10.58	11.66	9.55	14.58	11.59
		w/o force	12.98	11.36	12.63	12.99	12.49
4	Real	w/o cap	4.98	4.50	7.01	5.22	5.43
		w. cap	13.59	7.98	10.00	9.13	10.18
	Virtual	w. force	9.68	11.22	9.33	13.96	11.05
		w/o force	11.68	11.54	11.60	12.35	11.79

w/o cap : without wearing finger cap
w. cap : wearing finger caps
w. force : with force feedback displayed by SPIDAR-8
w/o force : without force feedback from SPIDAR-8

4.1. Experimental

Each sphere made by wood was 4.5cm in radius and weighted 200g. There were four different color of circular markers painted on the surface of each sphere. Two virtual spheres also had the same physical properties, radius and weight, as the real spheres.

Four male subjects were asked to perform this experiment. Two of them, subject A and B, had some experience of using SPIDAR-8, but the rest, subject C and D, did not have experience of using any haptic interface device before. However, before the trial, all subject were allowed to do some practices about 10 minutes with SPIDAR-8.

The subjects were asked to perform each trial of the experiment with four different constraints, i.e., performing with real spheres without wearing finger cap, performing with real spheres but wearing finger cap, performing with virtual spheres

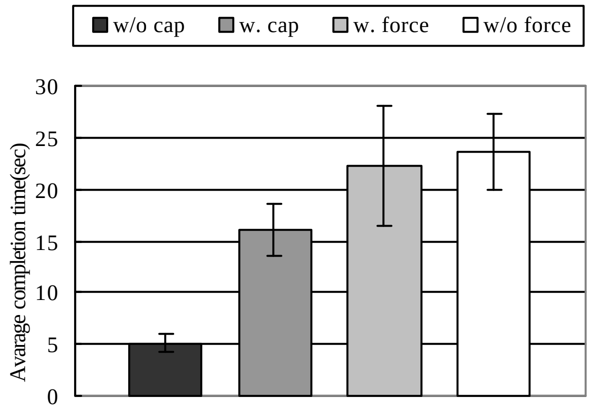

Fig. 9 Average completion time of 2 fingers

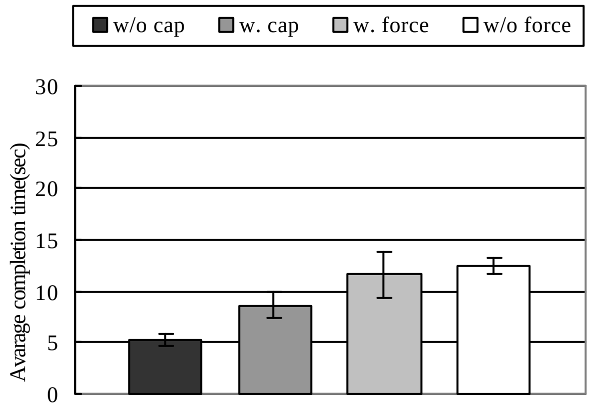

Fig. 10 Average completion time of 3 fingers

with force feedback provided by SPIDAR-8, and performing with virtual spheres by using SPIDAR-8 but without force feedback. Also in each trial, the subjects were asked to use different number of finger on each hand, i.e., two fingers, three fingers, and four fingers, for each constraint.

The task of this experiment was described to all subjects. At the beginning of each trial, each sphere was placed at its initial position and orientation. The subject had to pick up each sphere by each hand. The subject was allowed to rotate each sphere freely to align the same color. After completed fitting all four pair of markers, the subject had to placed each sphere back to its initial position and released the grasp. The completion time performed in different constraints had been recorded.

4.2. Results

Table 2 summarizes the results from the experiment. The average completion time performed by using two fingers, three fingers, and four fingers under different constraints of each subject are shown. The last column of the table shows the overall average completion time computed from all four subjects. Fig.9, Fig.10, and Fig.11 show graphs of the average completion time using different number of finger. Fig.12 shows a graph of the overall average completion time.

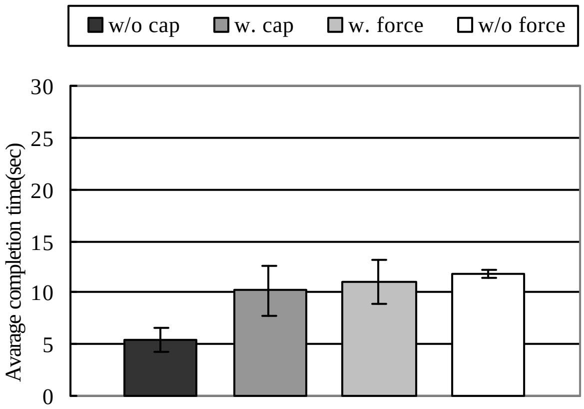

Fig. 11 Average completion time of 4 fingers

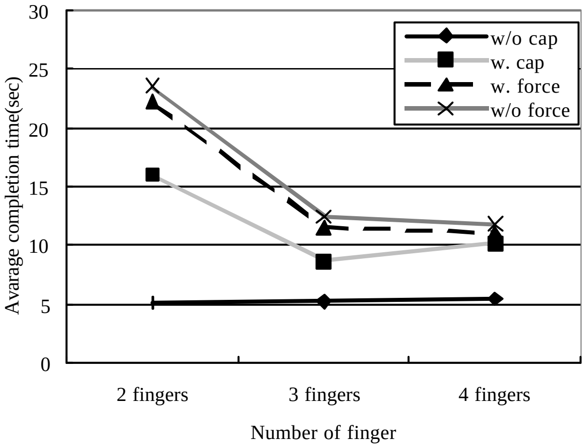

Fig. 12 Average completion time of Fit-The-Face task from all subjects

In the case of using two fingers, the trials with SPIDAR-8 takes about 4.5 times longer time than without wearing finger cap. However, the completion time with the use of three or four fingers became shorter than the use of two fingers. The subjects reported that using two fingers with SPIDAR-8 was difficult to grasp the virtual spheres stably. The cause of their difficulties was a problem of the equilibrium of forces in the virtual sphere. By using two fingers, it was difficult to apply equilibrium forces. However, by grasping with three or four fingers, the virtual sphere can be grasped more stable because of the distributed positions of grasping could maintain better equilibrium of forces. The differences of completion time using three and four fingers were not significant. However, we could often distinguish in the trials that the subjects could grasp the virtual sphere more stably by four fingers than by using three fingers. It could be led to a conclusion that by using multi fingers, three or four fingers on each hand, the manipulation of the virtual objects could be performed effectively.

In the cases of real spheres, there were two constraints, wearing the finger caps and without wearing any finger cap. By wearing the finger caps, the surface area at each fingertip of the subject

Table 3 Average penetrate depth of fingertip position into the virtual spheres

No. of Finger	Constraint	Average penetrate depth(mm)				Overall
		A	B	C	D	
2	w. force	5.23	2.89	7.23	4.93	5.07
	w/o force	18.86	14.78	12.52	13.69	14.96
3	w. force	2.98	1.61	6.94	2.05	3.40
	w/o force	18.16	12.33	8.96	16.43	13.97
4	w. force	2.15	1.39	5.95	1.96	2.86
	w/o force	8.38	7.36	8.12	16.17	10.01

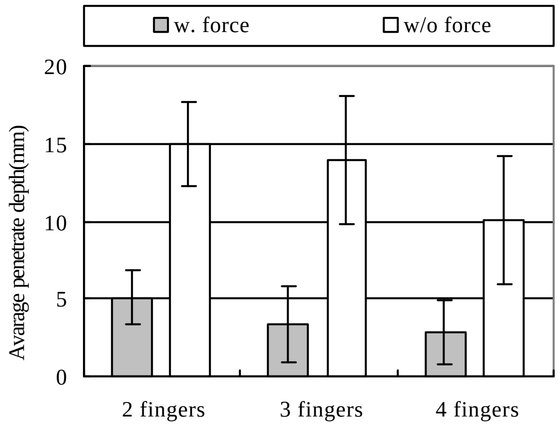

Fig. 13 Average penetrate depth into the virtual spheres

was largely reduced. It became difficult to grasp the real spheres stably. Because of this difficulty, the subjects spent as much completion time as using SPIDAR-8.

The trajectories of fingertip positions performing with the virtual spheres by using SPIDAR-8 were also recorded. In Fig.13, the average penetrate depth of fingertip position into the virtual spheres are shown. Compared the case using two fingers with the case using three or the four fingers, we can see that the fingertip in the case of using two fingers deeply penetrate the object. In few fingers, the users had grasped the object strongly to stabilize it.

5. Conclusions

There are still many works left for the future development of this haptic device. Force display capability of SPIDAR-8 has been a cause that limits several natural and realistic simulation of the virtual objects manipulation. We need to implement a control mechanism of balancing force to display force feedback smoothly when a finger changes from a position that can realize force to position that cannot realize force. The accuracy of sensing position of fingertips should also be improved. The revision of calibration method of all sensing fingertips, the precise connections of actuators to the frame, and the fitted-size of finger caps can further reduce the error of position sensing. The improvement of device efficiency should be beneficial to many diverse applications.

References

1. T. M. Massie and J. K. Salisbury, "The PHANToM Haptic Interface: A Device for Probing Virtual Objects", *Proceedings of the ASME Dynamic Systems and Control Division*, DSC-Vol. 55-1, pp. 295-301, 1994.

2. M. Andrenucci, M. Bergamasco, and P. Dario, "Sensor-based Fine Telemanipulation for Space Robotics", *Proceedings of NASA Conference on Space Telerobotics*, vol. 4, pp. 101-107, 1989.

3. S. Walairacht, M. Ishii, Y. Koike, and M. Sato, "Two-handed Multi-fingers String-based Haptic Interface Device", *IEICE Transactions on Information and Systems*, vol. E84D, no.3, pp. 365-373, March 2001.

4. S. Walairacht, K. Yamada, S. Hasegawa, Y. koike, and M. Sato, " Two-handed Multi-fingers Virtual Object Manipulation with Haptic cue", *Transactions of IEICE-DII*, vol. J84-D-II, no. 6, pp. 1140-1148, June 2000. (written in Japanese)