Proceedings of the 2002 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
EPFL, Lausanne, Switzerland • October 2002

Multi-Fingered Exoskeleton Haptic Device using Passive Force Feedback for Dexterous Teleoperation

Tatsuya Koyama[1], Ikuo Yamano[2], Kenjiro Takemura[3], Takashi Maeno[4]

[1]*Keio University, Yokohama, Japan, tkoyama@mx1.ttcn.ne.jp*
[2] *Keio University, i-yamano@dd.catv.ne.jp*
[3] *Keio University, kenjiro@mmm-keio.net*
[4] *Keio University, maeno@mech.keio.ac.jp*

Abstract

A novel control methodology for master-slave systems using passive force feedback has been proposed by the authors. The methodology solves the conventional problems of previously developed master-slave systems with force feedback, such as oscillations, complex structures and complicated control algorithm. In the present paper, a multi-fingered exoskeleton haptic device (master hand) with passive force feedback function is developed. First, the exoskeleton master hand with three fingers (12 degrees of freedom) is designed and implemented. Each finger of the master hand consists of a link mechanism with elastic-shaft joints and clutches. Using link mechanisms, the master hand measures fingertip positions and angles of index finger, middle finger and thumb. Furthermore, it also enables passive force feedback to an operator by the same link mechanism used for the geometric measurements. Then, a virtual reality system of human hand is constructed using the master hand and the control methodology. Using the system, sensory evaluations are conducted on human subjects to confirm the usability of the developed master hand and the possibility of the control methodology in the virtual reality system. As a result, the subjects possibly recognize the stiffness of the objects in the virtual environment.

1. Introduction

Human hands enable the dexterous manipulations such as handling tools, fabrication, and drawing. Generally, the dexterous manipulations are so complicated that it takes much time to be skilled. Especially, the skillful manipulations are needed in extreme environments including a nuclear reactor and space in these days. Hence, a device capable of measuring the fingers' motions and presenting the reaction force to the operator is desired. The device can be used for a motion capture of skilled dexterous manipulation, and as an input device for a remote control system, so to say a master-slave system. We name such a haptic device a “master hand” in this paper. For the past decade, several master hands have been developed and now in practice [1]-[9]. However, there are several problems in the conventional master hands as follows.

(1) Their entire systems are large in size.
(2) There are hindrances of natural finger operations by limits of movable area.
(3) The positions and the angles of fingertips are not accurately measured.
(4) When a wire drive is used for force feedback, there possibly exist friction, expansion, contraction of the wire, and delay.
(5) The force feedback is applied to unexpected parts of hand as well as to the fingertips.

(1)-(3) are the problems from measurements of geometry of fingertips, and (4)-(5) are from force feedback. Furthermore, there are needs for different mechanisms for measurements and force feedback in most of the previous devices. Therefore, it is necessary to develop a new type of master hand which solves the problems as (1)-(5) which enables us to fulfill both geometric measurements of fingertips and force feedback to the operators.

In the present study, a novel multi-fingered exoskeleton master hand is developed. The master hand solves the above-mentioned problems by use of link mechanism consists of serial and parallel link structures. The force feedback mechanism is designed using a master-slave control methodology with passive force feedback proposed by the authors [10]. The methodology provides the operator a master-slave operation with passive force feedback by simple mechanism and control algorithm using electromagnetic clutches and elastic elements. Its feature is to switch position/force controls according to the condition whether the slave robot is in contact with an object or not. So, the methodology has merits of both unilateral and bilateral master-slave control methods. Using the developed master hand and the control methodology, a virtual reality system of simple hand model in virtual space is also constructed as one of its applications. Then, the sensory evaluation using the system is conducted to confirm the usability of the master hand and the control methodology.

In this paper, the control methodology proposed in our previous study is briefly introduced in chapter 2. The structure of the master hand and the methods for geometric measurement and reaction force measurement are mentioned in chapter 3. Then, the virtual reality (VR) system is described in chapter 4, and sensory evaluation using the system is presented in chapter 5. Finally in chapter 6, the conclusions of this study are presented.

2. Control Methodology

2.1 Outline

Previously developed control methods for master-slave robots are divided into two categories; a unilateral control system and a bilateral one. The bilateral control system performs a force control in addition to a position control as shown in Figure 1(a). The force feedback using actuator such as electromagnetic motor enables dexterous manipulation on tele-robotics. However, there is a potential problem that the entire system becomes much complicated and expensive compared with unilateral control system. Furthermore, instability of force feedback occasionally occurs due to electrical noise. Therefore, we propose a new type of master-slave control methodology. It gives stable force feedback to the operator passively for realizing operation with sense of force by simple control algorithm and structure using clutch and elastic elements. The methodology is based on completely different idea from other studies [11], as shown in Figure 1(b), which is based on the control by switching position and force control according to contact condition of slave manipulator. The outline of the system is shown in Figure 2. Here, it has only single- DOF for brief explanation of the methodology. A master device consists of an encoder, an arm, an elastic element, a clutch and a shaft. The one side of the axis of the clutch is connected to the rotational axis of the device. The other side is fixed. A slave system consists of two encoders, an arm, an elastic element, a motor and a shaft. k_1 and k_2 represent torsion spring coefficients of the elastic elements. The elastic elements are used as one of the features of the system. An elastic factor is not generally thought to be a suitable factor for precise system, however, we dare to pay attention to elasticity for novel master-slave systems.

2.2 Procedure

2.2.1. Non-Contact Period

First, the angular positions, θ_1, θ_2 and θ_3, are obtained using the encoders. Then, θ_2 and θ_3 are compared with each other in order to distinguish whether the slave arm is in contact with arbitrary object or not, i.e., they become different when the arm is in contact with the object according to the deformation of the elastic element. During the period when the slave arm is not in contact with any object, the clutch is operated to be unlocked for the angular position of the slave arm (θ_3) to be controlled to agree with that of the master arm (θ_1) using a position controller. Then, the elastic elements do not deform because the end of the elements are completely free.

2.2.2. Contact Period

When the slave arm starts to contact with an object, the control method is switched to the force control according to Table 1. During the contact period, the clutch is operated to be locked, and the reaction force the operator feels is reproduced at slave arm. This is where the elastic element in the master device comes into play.

The clutch in the master system is locked just after the slave arm get in contact with the object, and the locked angular position is memorized as θ_1'. The angles of torsion of elastic elements for the master and slave systems are obtained using θ_1, θ_1', θ_2 and θ_3. When the elastic element of master device is twisted by the operator's pressing force, the operator feels passive reaction force represented by ($k_1 \cdot (\theta_1 - \theta_1')$). If the ($\theta_2 - \theta_3$) is larger than the threshold decided in advance, it is controlled using the motor in the slave system to be ($k_1 \cdot (\theta_1 - \theta_1') = k_2 \cdot (\theta_2 - \theta_3)$). Namely, the operator only feels the passive reaction force by the torsion of the elastic element without active ones. Then, the operator does feel the reaction force generated in the slave arm without feeling any oscillations of the master arm caused by the electrical characteristics.

It can be argued that the angular positions of the master and slave arms during the contact period are different if the stiffness of the object is different from that of the elastic element in the master device. There is, however, a fascinating report for influence of visual sensation under the master-slave system [12]. The report says that humans mainly perceive the stiffness of objects from the combination of visual

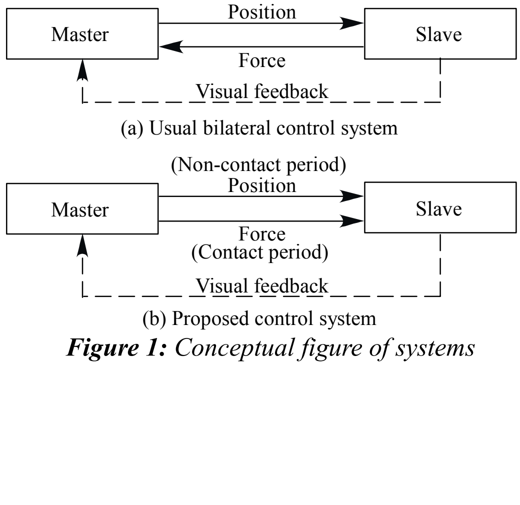


Figure 1: *Conceptual figure of systems*

Table1: *Method of the switching of control*

	Non-contact period	Contact period
Clutch	Release	Lock
Ultrasonic motor	Controlled to be $\theta_1 = \theta_3$	Controlled to be $k_1 \cdot (\theta_1 - \theta') = k_2 \cdot (\theta_2 - \theta_3)$
Control method	Position control	Force control

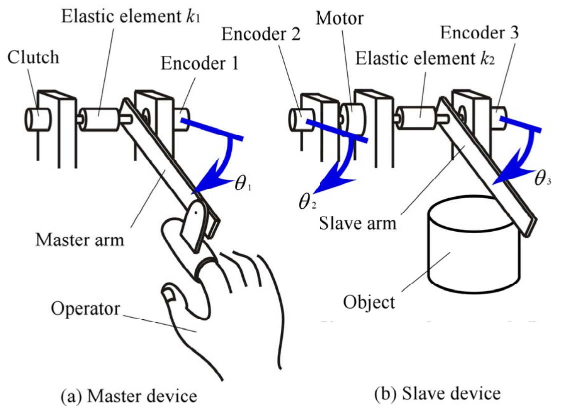


Figure 2: *Outline of proposed system*

displacement and haptic force information, whereas the direct displacement information is rarely used. Hence, the proposed method is thought to make the operator perceive the stiffness of objects using visual feedback. Furthermore, if the torsional rigidities of elastic elements in the master and slave systems are selected to be different, reaction force can be scaled using the same methodology. Whenever the object does not move actively, the method is useful, while the method cannot provide the reaction force when the object moves because the information about reaction force is sent from the master device to the slave device as shown in Figure 1. This method is especially suitable for tele-operation having time delay, for example, operation by use of internet, because instability due to the delay of force feedback never occurs since no control signal is sent from the slave device to the motor driver of the master device as shown in Figure 1(b). Although the above explanation is based on the single-DOF system, the proposed methodology can be easily extended to a multi-DOF system because the whole master-slave system consists of simple components. It also can be applied to VR system with which the slave device is set in the virtual space.

3. Multi-Fingered Master Hand

3.1 Design and Manufacture

The input/output system with the multi-fingered master hand is expected to be used for dexterous operations including precise assembling. Since fingertips are mainly used for the tasks, only the positions and reaction forces of each fingertip may be measured. Exoskeleton type devices with links mechanism are suitable for solving the problems (1)-(5) mentioned above.

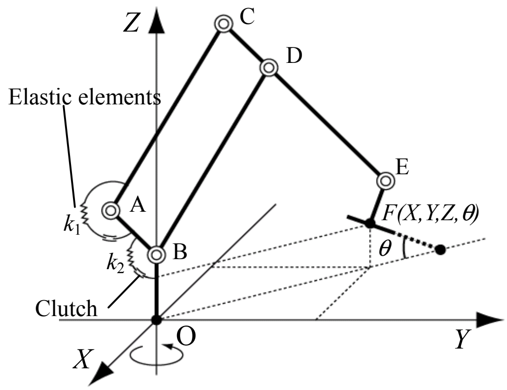


Figure 3: *Outline of the master hand*

The master hand is composed of the serial link for measuring the position of fingertips and parallel links for force feedback as shown in Figure 3. The quadrangle ABDC forms the parallelogram with single-DOF of rotation around the *z*-axis at point O. A four-DOF motion per finger can be measured using the master hand, where, the position and posture of each fingertip can be completely measured. The angle of each link is obtained from the angle sensor at B, C, E and O. Then, the position and posture of each fingertip are calculated using forward kinematics. Therefore, problem (3) is solved.

Passive force feedback at the fingertip is conducted using clutches and spring at A and B. The clutches and springs are shown schematically in Figure 3. They are actually placed in series at the same axle as the rotational axes. The clutch at A and B lock and unlock the link AC with AB and AB with BO, respectively. Elastic torsion springs are connected with shafts of each clutch in order to adopt the above-mentioned control method. The force given to the fingertips can be calculated from the angles of links and torsion spring coefficient of the elastic elements. As the clutches for the force feedback are located near the base, their weight has little influence on the operator's manipulation. The reaction forces can be displayed only at the fingertips then, problem (5) is solved because the links are only fixed at the fingertips and the back of hand. The problem (4) is also solved because link mechanism is used not only to measure the geometry of fingers but also to provide the force feedback.

Moreover, the structure of the master hand is so simple that it is easy to manipulate. This solves problem (1).

An experimental device of the master hand is shown in Figure 4. The acrylic plates, potentiometers and acrylic shafts are used as link components, angle sensors and elastic elements, respectively.

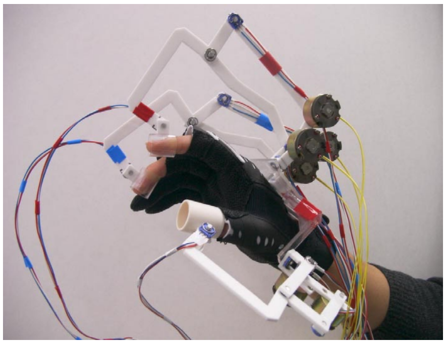


Figure 4: *Multi-fingered master hand*

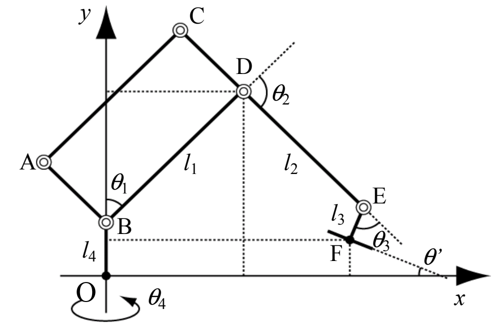
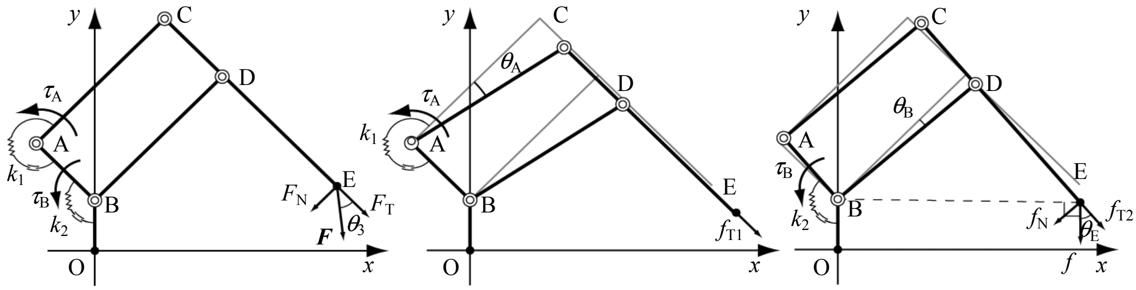


Figure 5: *2-D geometrical model of the master hand*



(a) Direction of torque and force (b) f_{T1} and τ_A (c) f and τ_B

Figure 6: *Outline of reaction force measurement*

Table 2: *Length of l_1-l_4 [mm]*

part	l_1	l_2	l_3	l_4
index	105	70	6	21
middle	105	70	6	21
thumb	55	70	6	16

3.2 Method and Results of Measurements

3.2.1. Geometric Measurement

The link mechanism has single-DOF of rotation at point O in Figure 3. Therefore, the master hand is regarded as two-dimensional model including θ_4. Two-dimensional model of the master hand is shown in Figure 5. The position and posture of the fingertip can be calculated by following equations.

$$x = l_1 \sin\theta_1 + l_2 \sin(\theta_1+\theta_2) + l_3 \sin(\theta_1+\theta_2+\theta_3) \quad (1)$$

$$y = l_1 \cos\theta_1 + l_2 \cos(\theta_1+\theta_2) + l_3 \cos(\theta_1+\theta_2+\theta_3) + l_4 \quad (2)$$

$$\theta' = \theta_1+\theta_2+\theta_3 - 90^\circ \quad (3)$$

where x, y and θ denote the position and angle on the x-y plane. Then, the position and angle of the fingertip can be calculated as

$$X = x\sin\theta_4 \quad (4)$$

$$Y = x\cos\theta_4 \quad (5)$$

$$Z = y \quad (6)$$

$$\theta = \theta' \quad (7)$$

where X, Y, Z and θ denote the position and angle in the XYZ space. The lengths of the links l_1-l_4 are shown in Table 2.

Next, the accuracy of the geometric measurement of the master hand is examined. As a result of experiments for measuring several positions of fingertip in the movable range, the maximum errors between the actual/calculated positions of index finger, middle finger and thumb are 3.05, 2.61 and 2.09mm, respectively. The errors are not small enough for the hand to be utilized for high precision operations, however, they can be improved using high-resolution sensors and links with high rigidity.

3.2.2. Reaction Force Measurement

The reaction force of the fingertip can be calculated from the angles and the torsion spring coefficient of the elastic elements. The outline of reaction force measurement is shown in Figure 6 (a)-(c). k_1 (2.42×10^{-2} Nm/deg) and k_2 (2.33×10^{-2} Nm/deg) are the spring coefficients of acrylic shafts. τ_A and τ_B that work against the bending/stretching motions of fingertips are applied in the direction as shown in Figure 6 (a). $\boldsymbol{F}$ shows the direction and the magnitude of the reaction force applied to the fingertip. $\boldsymbol{F}$ is divided into tangential component F_T and normal component F_N as shown in Figure 6 (a). F, F_T and F_N are calculated as follows.

$$F_T = F\cos\theta_3 \quad (8)$$

$$F_N = F\sin\theta_3 \quad (9)$$

$$F = \sqrt{F_T^{\,2} + F_N^{\,2}} \quad (10)$$

The force applied to the fingertip and the torque applied to the elastic elements are balanced as shown in Figure 6 (b) (c).

$$\tau_A = k_1\theta_A \quad (11)$$

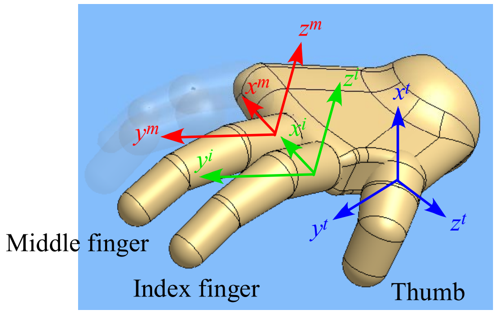


Figure 7: *Reference frames for each finger [12]*

$$\tau_B = k_2 \theta_B \tag{12}$$

where τ_A and τ_B are torsion angles. It is assumed that the angle between link AB and BO is constant in the Figure 6 (b). Hence, f_{T1} is calculated as follows.

$$f_{T1} = \tau_A / l_1 \tag{13}$$

It is also assumed that the angle between link AB and AC is constant in the Figure 6 (c). Hence, f, f_{T2} and f_N are calculated as follows.

$$f = \tau_B / BE \tag{14}$$

$$f_{T2} = f \cos\theta_E \tag{15}$$

$$f_N = f \sin\theta_E \tag{16}$$

Therefore, F is obtained as follows.

$$F = \sqrt{(f_{T1} + f_{T2})^2 + f_N^{\ 2}} \tag{17}$$

Then, the accuracy of the reaction force measurement at the master hand is examined. The maximum error was 0.20 N in measuring the reaction force passively applied to the fingertip. It is about 6.7 % of maximum reaction force generated in the master hand calculated from the holding torque of the clutch, 0.25 Nm.

4. VR System

The VR system using the master hand utilizing passive force feedback is constructed as one of the applications in this chapter. The position and the angle of the fingertip obtained using the master hand is used as an input for the system. A hand model in virtual space displayed on LCD is an output from the system.

Output signal from each potentiometer is supplied to the PC through an A/D converter (CONTEC, AD12-8 (PM)). The signals are converted to the angular positions and the angle of the fingertip. Then, each joint angle of the hand model is calculated from the position and the angle of the fingertip by use of inverse kinematics. The commands from the PC to switching circuit for the clutches are sent through a D/A converter (CONTEC, AD12-8 (PM)). Reference frame for each finger is fixed at the base of finger as shown in Figure 7.

In the virtual space, wall for each finger is defined. The walls are located at ($z = -50$ [mm]) for each frame of reference with linear spring along the z-axis, although they are not displayed on the LCD. Namely, both clutches for the corresponding finger in the master hand work together to provide passive reaction force to the operator when the fingertip of hand model is in contact with the wall. It is regarded as contact as the fingertip cross the wall followed by finger movement. The displacements of the fingers of hand model are defined as balance of the reaction force and the spring force while they are in contact with the wall.

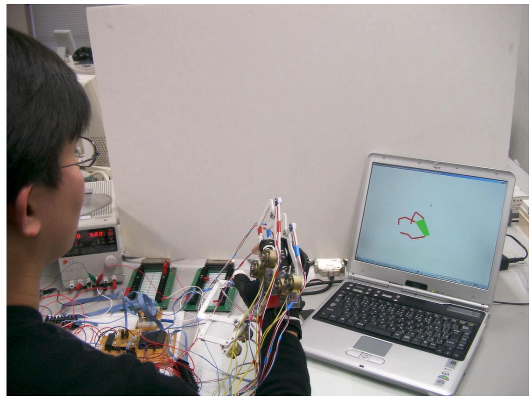


Figure 8: *Sensory evaluation using VR system*

5. Sensory Evaluation

Sensory evaluations were conducted using the VR system in order to verify the availability of the proposed system. The outline of the sensory evaluations is as follows.

(1) Nine walls with different stiffness were prepared in the virtual space. The spring coefficients of each wall, A to I, were 0.116, 0.125, 0.131, 0.138, 0.189, 0.196, 0.206, 0.216 and 0.316 N/mm, respectively.

(2) Subjects were asked to identify which stiffness was larger than the other for 14 pairs selected from the nine walls using the developed system.

(3) Sensory evaluation (2) was conducted twice on one subject in random order.

(4) Subjects were also asked to select a wall whose displacement looked the same as that of his/her finger.

The sensory evaluations were conducted on eight subjects. The view of sensory evaluation is shown in Figure 8. Table 3 (a)(b) show the results for the sensory evaluations. Table 3 (a) shows the comparison among subjects. Table 3 (b) shows the comparison between the different stiffness. Although the ratio of correct answers for subjects 7 and 8 were not large, the average ratio of correct answer, 0.82, was sufficiently large. The results of the experiment (4) were not uniform for each subject, although the position of the master hand and the hand model

***Table 3:** Results for sensory evaluations*

(a) Comparison among subjects

Subjects	Percentage of correct answers [%]	Wall selected in experiment (4)
1	89	D
2	86	E
3	89	B
4	82	B
5	86	C
6	93	A
7	61	B
8	71	C
Average	82	

(b) Comparison of the difference in stiffness

Difference of stiffness [N/mm]	Average of ratio of correct answers
0.006	0.69
0.007	0.50
0.009	0.94
0.013	0.56
0.015	1.00
0.022	0.94
0.051	0.69
0.058	0.56
0.064	0.75
0.073	1.00
0.080	1.00
0.090	0.94
0.100	1.00
0.200	0.94

become equal in case of the pattern B. It indicates that the visual sensation is more important than the direct detection of the displacement due to the kinesthesia to perceive the displacement of the fingertip. The result agrees well with the previously reported result [13]. Table 3 (b) suggests the minimum resolution of the stiffness. Ratios of correct answers were not always large enough in case the difference of stiffness was smaller than 0.058 N/mm. When it was larger than 0.064 N/mm, the ratio was almost 1.00. As a result, the resolution of stiffness using the developed master hand was around 0.07 N/mm. Resolution can be improved with high-accuracy angle sensor and high rigidity of links.

6. Conclusions

The multi-fingered exoskeleton master hand with passive force feedback for tele-operation is developed in the present study. The position and the angle of the tip of index finger, middle finger and thumb are measured using the master hand. We dare to use elastic elements in it to provide passive reaction force to the operator. From the sensory evaluation using the VR system constructed using the master hand and tele-operating control method developed in our previous study, it is confirmed that the subjects can identify the stiffness of wall in the virtual space using the system when the difference in the stiffness is larger than a certain value.

Future study focuses on building precise hardware and sensors, and developing five-fingered master-hand. Future study also focuses on development of multi-fingered slave hand and constructing master-slave system capable of generating dexterous manipulation.

Acknowledgement

This study was supported in-part by [a Frontier Research from Keio Leading-edge Laboratory of Science and Technology]. This study was also supported in-part by [a Grant-in-Aid from the Regional Science Promotion Program in Kanagawa].

References

[1] http://www.immersion.com/

[2] http://www.sensable.com/

[3] Gomez, D., G. Burdea, and N. Langrana, "Integration of the Rutgers Master II in a Virtual Reality Simulation", *IEEE Virtual Reality Annual Int. Symp. (VRAIS)*, pp.198-202, 1995.

[4] S. C. Jacobsen, E.K. Iversen, D. F. Knutti, R.T. Johnson and K. B. Biggers, "Design of the Utah/MIT Dexterous Hand", *Proc. IEEE Int. Con. Robotics and Automation*, IEEE, pp.1520-1532, 1986.

[5] http://www.cs.utah.edu/classes/cs6360-jmh/Nahvi/haptic.html#rm1

[6] http://www.sarcos.com/

[7] Grigore C. Burdea, *Force and touch feedback for Virtual Reality*, John Wiley & Sons, Inc., New York, 1996.

[8] T. Kitada, Y. Kunii and H. Hashimoto, "20 DOF Five Fingered Glove Type Haptic Interface –Sensor Glove II-", *J. Robotics and Mechatronics*, Vol.9, No.3, pp. 171-176, 1997.

[9] Bruno M. Jau, "Dexterous Telemanipulation with Four Fingered Hand System", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 338-343, 1995.

[10] I. Yamano, K. Takemura, K. Endo and T. Maeno, "Method for Controlling Master-Slave Robots using Switching and Elastic Elements", *Proc. IEEE Int. Conf. Robotics and Automation*, IEEE, 2002.

[11] K. Fukusumi, M. Sakaguchi, J. Furusho, "Basic Study on PassiveForce Display", Proceedings of the 43nd Annual Conference of the Institute of Systems, Control and Information Engineers, ISCIE, pp. 305-306, 1999

[12] http://www.cbliss.com/

[13] M. A. Srinivasan, G. L. Beauregard and D. L. Brock, "The impact of visual information in the haptic perception of stiffness in virtual environments", *Proc. ASME Dynamic System and Control Div.*, DSC, vol.58, pp.555-559, 1996.