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Development of Five-Fingered Haptic Interface: HIRO-II

Haruhisa Kawasaki, Tetsuya Mouri, M. Osama Alhalabi, Yasutaka Sugihashi, Yoshio Ohtuka, Sho Ikenohata, Kazushige Kigaku, Vytautas Daniulaitis, Kazuyasu Hamada, and Tatsuo Suzuki
Gifu University, 1-1 Yanagido, Gifu, 501-1193, Japan
h_kawasa@cc.gifu-u.ac.jp

Abstract

This paper presents the design and the characteristics of a new developed five-fingered haptic interface robot named HIRO II. The haptic interface can present force and tactile feeling at the five fingertips of the human hand. It is designed to be completely safe and similar to the human upper limb both in shape and motion ability. Its mechanism consists of a 6 DOF arm and a 15 DOF hand. The interface is placed opposite to the human hand, which brings safety and no oppressive feeling, but this leads to difficulty in controlling the haptic interface because it should follow the hand poses of the operator. A redundant force control method in which all the joints of the mechanism were force controlled simultaneously to present the virtual force is studied. Experimental results to show high potential of a multi-fingered haptic interface are presented.

Key words: Haptic interface, Force control, Redundant control, Virtual reality

1. Introduction

Haptic interfaces that present force and tactile feeling have been utilized in the area of tele-manipulation [1]-[4], interaction with micro/nano scale phenomenon [5] [6], medical training and evaluation [7]-[9], and so on. Multi-fingered haptic interface has a higher potential for the above mentioned applications than that of single point haptic interfaces. Several multi-fingered haptic interfaces [10]-[16] have been developed. Haptic interface consisting of an arm and fingertips haptic display [14]-[16] can be used in a wide space. However, the issue of developing a haptic interface opposite to the human hand was never addressed. The haptic interface is demanded to be safe, work in wide operation space, and to present not only force at the contact points but also weight feeling of virtual objects. In addition, it should not have an oppressive feeling when it is attached to humans, also do not have weight feeling of itself. We have developed a three fingers haptic interface named HIRO [17]-[18] to solve these issues. HIRO has demonstrated the suitability as a multi-fingered haptic interface opposite to the human, but it has only three fingers. The control of HIRO has combined the force control of the fingers and the position control of the arm, in which desired hand posture was decided to get the maximum manipulability of the hand. This method allows HIRO to respond to various operator's hand poses. However, according to this control method a large motion of the arm may occur even though the fingers' motions are small. This excessive motion sometimes may disturb an operator creating an illusion of malfunctioning. A redundant force control method is studied to solve this problem. There are many researches on redundant manipulators [19]-[20]. But, redundant force control with condition of contacting to multi fingers of human has been never addressed.

This paper presents a new developed five-fingered haptic interface robot named HIRO II. The interface is placed opposite to the human hand, and the haptic fingertips are connected to the human fingertips through passive spherical permanent magnet joints. For presenting haptic feeling in wide operation space and providing the sense of security, a redundant force control is implemented. In this control approach all joints of the mechanism are simultaneously force controlled to display a virtual force to the five fingers. The experiments are presented to show the high potential of the multi-fingered haptic interface.

2. Design of the HIRO-II

2.1 Basic design

Multi-fingered haptic interfaces joined to the arm can provide a wide operation space. But, most of them are mounted on the back of the human hand like the CyberForce [16]. Fixing the haptic interface to the hand gives oppressive feeling to the operator since the interface binds the human hand firmly. In order to reduce the oppressive feeling and increase safety, a three-fingered haptic interface opposite to human hand has been presented by our group [17]. Now, we developed a new Haptic Interface RObot named HIRO II

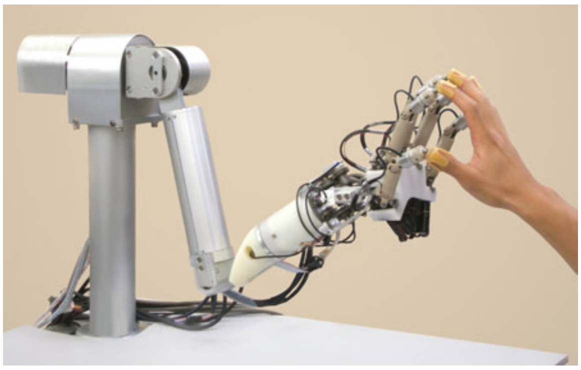


Fig. 1 The Developed five-fingered haptic interface: HIRO II

to present force feeling to all human hand fingers. Fig. 1 shows the developed five-fingered haptic interface, where it is connected to the five fingers of an operator hand. The haptic interface consists of an interface arm, a haptic hand with five haptic fingers, and a controller. When the operator moves his/her hand, the haptic interface follows the motion of operator's fingers and present the force feeling. The operator feels just a little oppressive feeling because the coupled part between the human hand and the haptic interface is only the fingertips of the operator.

2.2 Haptic hand

The haptic hand starts from the wrist but does not include it, and ends with the fingertips. A hand base, and five haptic fingers form the haptic hand as shown in Fig. 2. The haptic fingers are designed to be similar to the human fingers in geometry and motion ability. Table 1 shows specifications of the haptic hand.

The developed haptic finger is shown in Fig. 3. It is designed based on an anthropomorphic robot hand, named Gifu Hand III [20]. Each finger has 3 joints allowing 3 DOF. The first joint, relatively to the hand base, allows abduction/adduction. The second joint allows flexion/extension. The third joint allows flexion/extension. All joints are driven by DC servomotors with gear transmissions and rotary encoders. The motion ranges from the 1st to the 3rd

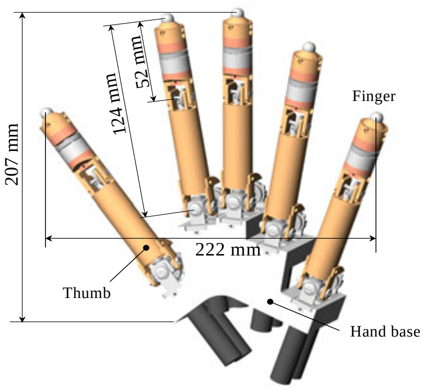


Fig. 2 Haptic hand design

Table 1 Specifications of the haptic hand

Hand	Number of fingers	5	
	Degree of freedom	15	dof
	Weight	0.73	Kgf
Finger	Degree of freedom	3	dof
	Weight	0.13	Kgf
	Workspace of thumb	713	cm^3
	Workspace of finger	535	cm^3
	Output force	3.5	N (max)
	Velocity	0.23	m/s (max)

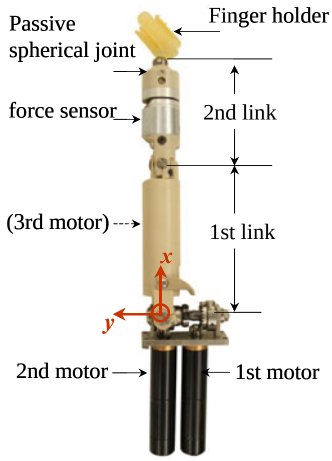
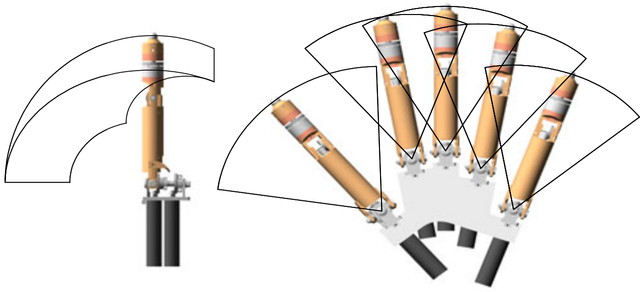


Fig. 3 Haptic finger

joints are –30 ~ 30, -25 ~ 94, and -10 ~ 114 [deg], respectively. Thumb is almost same as the above mentioned finger except for a reduction gear ratio and movable ranges of the joint 1 and joint 2. The motion ranges from the 1st to the 2nd joints of the thumb are –40 ~ 40 and -25 ~ 103 [deg]. Workspaces of the thumb and hand are shown in Fig. 4(1) and Fig. 4(2). Volumes of the workspace of the thumb and fingers are 535 and 713 [mm^3], respectively. The thumb is designed to work in wide space because the workspace of the human's thumb is larger than that of the other fingers. Finger layout of the haptic hand is designed to maximize the volume formed by intersecting workspaces of the haptic and human fingers. For example, this volume (we also call it product space) for the haptic and human index fingers has its maximum at the posture shown in the



(1) Thumb (2) Hand

Fig. 4 Workspaces of thumb and hand

Fig.5. In this case, workspaces of the human index finger and the haptic finger are 281 and 535 [cm^3], respectively. The product space at the optimum pose is 259 [cm^3]. The haptic index finger was designed basing on the statistical data of Japanese males, that is, the lengths of distal, middle, and proximal phalanxes are 39, 20, and 26 [mm], respectively. The allocation of fingers in haptic hand was designed in consideration of this geometrical relation.

Another important issue in haptic finger design is selection and installation of the force sensors. In order to read the finger loading, the 6-axes force sensor (NANO sensor by BL AUTOTEC. LTD.) in the second link of each finger is installed. To manipulate the haptic interface user has to wear a finger holder on his/her fingertips (see Fig.6). Finger holder has a sphere which, attached to the permanent magnet at the force sensor tip, forms a passive spherical joint. This passive spherical joint has two roles. One, is the adjustment of differences between the human and haptic fingers orientations. Each human finger has 6 DOF and each haptic finger has 3 DOF. Hence, additional passive 3 DOF are needed. Two, is to ensure the operator can take off his fingers from the haptic interface when it malfunctions. The suction force by the permanent magnet is 5 [N].

The maximum output torques of the 1st, 2nd, and 3rd joints are 0.81, 0.43, and 0.2 [Nm] respectively, which provide force on a fingertip of 3.4, 3.4, and 6.5 [N] along axes X, Y and Z in finger coordinate system (see Fig.3). The maximum velocities from the joint 1st till 3rd are 1.9, 3.5, and 9.2 [rad/s] respectively, which are equivalent to fingertip velocities v_x, v_y, v_z of 0.43, 0.43, and 0.23 [m/s] respectively. These specifications show that the haptic finger can follow the human finger motion in task execution.

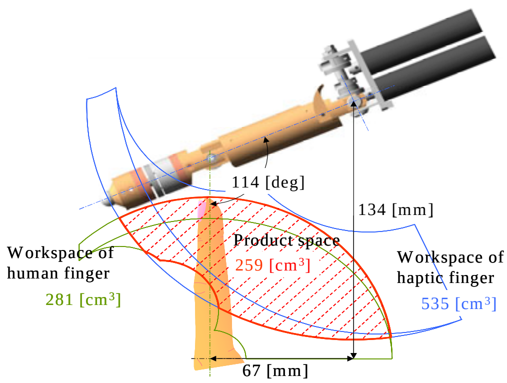


Fig.5 Optimum pose of the haptic finger for the human finger

Fig. 6 Finger holder

2.3 Interface arm

The interface arm is designed to be as close as possible to the human arm in geometry and motion ability as shown in Fig. 7. The upper joint of the interface arm is the shoulder joint. The shoulder joint motion is simplified to 2 DOF because the third DOF's contribution to the interface arm flexibility is too limited relatively to the complexity of realizing it. The two possible DOF are the shoulder flexion/extension and shoulder adduction/abduction, and the neglected DOF is the shoulder radial/lateral rotation. The middle joint of the interface arm is the elbow joint with 1 DOF, which generates the elbow flexion/extension. The lower joint of the interface arm is the wrist joint with 3 DOF. The first DOF is the forearm supination/pronation, the second DOF is the wrist flexion/extension, and the third DOF is the wrist abduction/adduction. The interface arm has therefore 6 joints allowing 6 DOF. The interface arm has a similar size to the human arm, and its joints motion ranges are compatible with it.

The lengths of the upper arm and the forearm are 0.3 and 0.31 [m], respectively. The arm joints are actuated by AC servomotors equipped with rotary encoders and gear transmissions. Movable ranges of the joint angles from 1st to 6th are (-180, 180), (0, 180), (-90, 55), (-180, 180), (-55, 55), and (-90, 90) [degrees]. Fig.8 shows the movable space and the work space of the haptic arm. The workspace is about 400x800x300 [mm]. Table 2

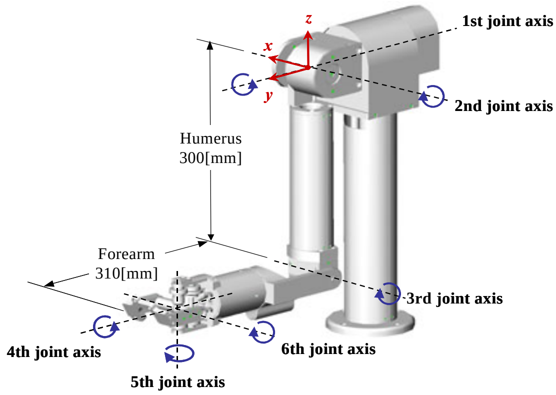


Fig. 7 Arm design

Table 2 Specifications of the haptic arm

Degree of freedom	6	
Output force	45	N
Output moment	2.6	Nm (max)
Transnational velocity	0.4	m/s (max)
Rotational velocity	1.4	rad/s (max)
Weight	6.9	Kgf

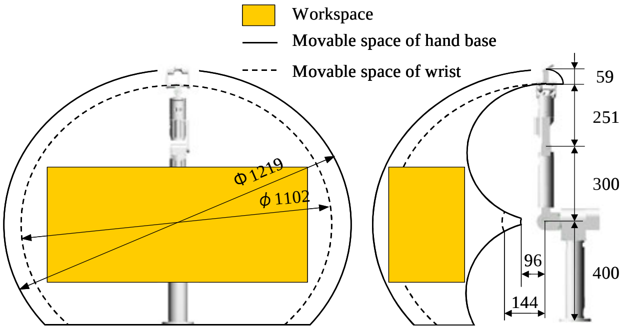


Fig.8 Workspace of the haptic arm

shows the specifications of the arm. The weight of the whole mechanism is 40% reduced compared with HIRO [17]. Maximum output force is 45 N and maximum velocity at haptic hand base is 0.8 [m/s].

3. Interface control

The control system of HIRO II is shown in Fig. 9. The control system consists of PC, 12 bits digital to analogue converter (D/A), 16 bits up/down counter (CNT), 12 bits analogue to digital converter (A/D), digital input and output (DIO), hand motor analog power amplifier, and arm motor PWM driver. Real time operating system Art-Linux [20] is adopted to guarantee 1 [ms] sampling time of the control. Table 3 shows examples of control commands for HIRO II. These commands are sufficient to control the robot at the haptic interaction.

In HIRO [17], the control was a combination of the force control of the fingers and the position control of the arm, in which desired hand posture was decided to maximize the manipulability of the haptic hand. However, the control algorithm sometimes may command the arm to move by big angles despite the small motion of the operator's fingers. To solve this problem, a redundant force control with multi-points interaction has been examined. A control input of the haptic interface by the redundant force control is given by

$$\boldsymbol{\tau} = \boldsymbol{K}_1 \boldsymbol{J}^T (\boldsymbol{F}_d - \boldsymbol{F}) + \boldsymbol{K}_2 \int \boldsymbol{J}^T (\boldsymbol{F}_d - \boldsymbol{F}) dt \qquad (1)$$

where $\boldsymbol{\tau} = (\boldsymbol{\tau}_{arm}{}^T, \boldsymbol{\tau}_{hand}{}^T)^T \in R^{21}$ is a joint torque vector whose sub vectors are an arm joint torque vector $\boldsymbol{\tau}_{arm} \in R^6$ and a hand joint torque vector $\boldsymbol{\tau}_{hand} = (\boldsymbol{\tau}_{thumb}{}^T, \boldsymbol{\tau}_{index}{}^T, \cdots, \boldsymbol{\tau}_{little}{}^T)^T \in R^{15}$, $\boldsymbol{J} \in R^{21\times 15}$ is a kinematic Jacobian, $\boldsymbol{F} = (\boldsymbol{F}_{thumb}{}^T, \boldsymbol{F}_{index}{}^T, \cdots, \boldsymbol{F}_{little}{}^T)^T \in R^{15}$ is a force vector whose sub vector is a force vector at finger tip. $\boldsymbol{F}_d$ is a desired force vector, $\boldsymbol{K}_1$ is a force feedback gain matrix, and $\boldsymbol{K}_2$ is a force integral feedback gain matrix. Most of redundant force control [17]-[18] have been examined only on a single constrained point at manipulator's end-effector. The proposed redundant force control works at multi contacting points. Each finger joints is controlled

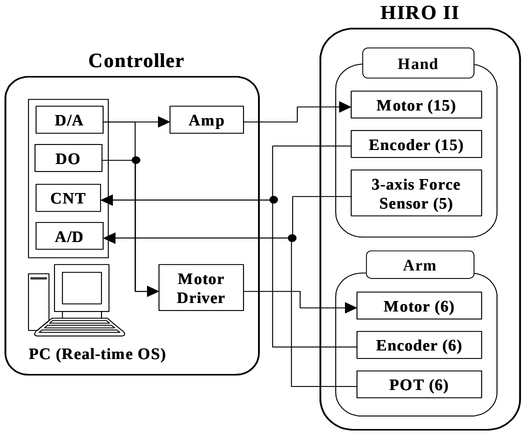


Fig. 9 Control system of HIRO II

Table 3 Examples of control commands

Commands	Function
hiro_open_dev	Open interface boards.
hiro_close_dev	Close interface boards.
hiro_setup_dev	Set up interface boards.
hiro_init_dev	Initialize interface boards.
hiro_get_angles	Measure joint angles.
hiro_out_torques	Output joint torques.
hiro_get_force	Measure fingertip forces.
hiro_set_origin	Set the origin point
hiro_control_pid	Control PID for joint angles.
hiro_cotrol_force	Control PI for fingertip forces.
hiro_control_torque	Control proposed method for fingertip forces and arm position.

to follow the desired finger force independently. The arm joint is controlled practically to follow desired force and moment at hand bases, which are generated by the desired finger forces. In this control, a finger that reaches the limit of the movable range is switched to a

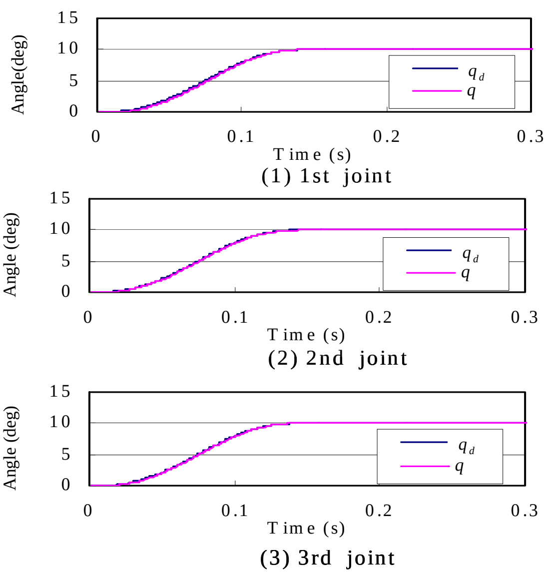


Fig. 10 Position responses of a finger

position control to keep the joint angle in the movable range, and the rest of fingers are controlled by the redundant force control. After reaching the limit of the movable range, the finger that switched to the position control is switched back again to the redundant control when the direction of the joint torque input is the same direction of that of the joint angle apart from the limit of the movable angle.

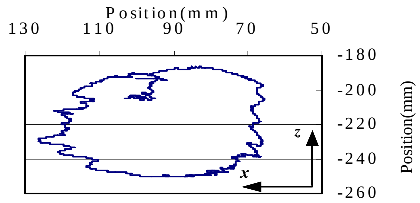
4. Experiment

4.1 Device performances

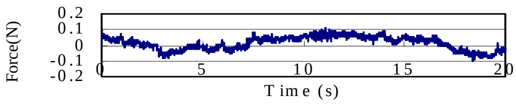
The improvement of hardware and software results in a new version of the HIRO with high potential for the haptic interaction. Position responses of finger are shown in Fig. 10. Desired trajectory is given by a 5-order polynomial in time with zero initial and terminal velocities and accelerations. These responses are enough for haptic interaction on a deskwork.

Responses of a finger by the force control in free space are shown in Fig.11. In this case, the index finger of human is connected to the haptic interface and desired force at finger is set to zero. Fig. 11(1) shows fingertip position in free space. Average force error is 0.08 N. It is significant improvement because the average force error was 0.2 N in HIRO [17].

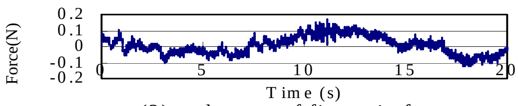
Responses of a finger by the force control in constrained space are shown in Fig.12. In this case, the index finger of human is connected to the haptic interface and pushes a virtual wall. A desired force at the finger is set to be $F_d = Kx + d\dot{x}$, where x is the penetration depth of the finger into the wall, K (= 2.0 [N/mm]) is the stiffness of the wall and d (=5.5x10^{-5} [Ns/mm]) is a damping coefficient of the wall. Average force error is almost the same as that in free space.



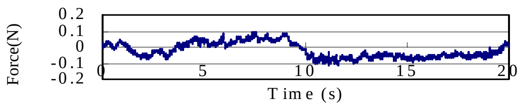
(1) Fingertip position



(2) *x* element of fingertip force



(3) *y* element of fingertip force

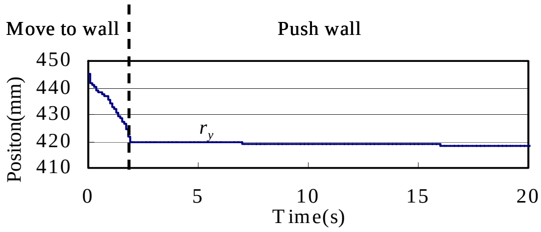


(4) *z* element of fingertip force

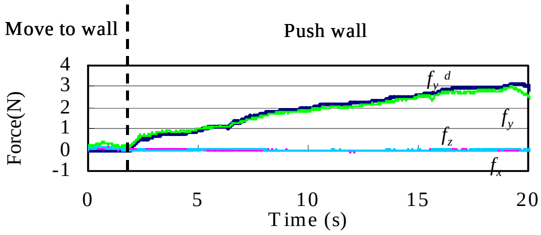
Fig. 11 Force responses of a finger in free space

4.2 Evaluation of manipulability

We have developed a future science encyclopedia (FSE) to show the power of sense on 5 human fingers by using HIRO II, which has been demonstrated during 9th to 19th of June in the prototype robot exhibition at World Expo 2005, Aichi, Japan [21]. The FSE has three worlds: planets in the solar system, the world of dinosaurs, and the micro world. One of the demonstration in the world of dinosaurs is shown in Fig. 13, in which the HIRO presents the touch of the skin of ancient creature (dinosaur). Operator uses a HMD (head mounted display) to see 3D graphics. Details of the FSE system will be submitted to the Symposium on Haptic Interfaces 2006 [22]. We kindly asked 29 users who operated the HIRO II at the EXPO to evaluate the manipulability of the robot. The results are shown in Fig. 14. Most of the users replied that it is not easy to operate the robot. One of the reasons was related to a not accurate distance perception from 3D graphics. Another reasons include deterioration of the haptic arm manipulability near kinematicly singular points and haptic arm vibration caused by low hardware stiffness. These are the problems to be solved in future. However,



(1) Fingertip position



(2) Fingertip forces

Fig. 12 Force responses in constrained space

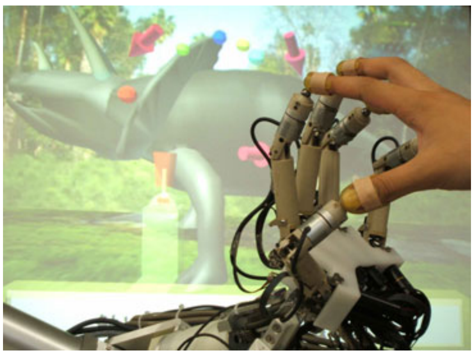


Fig. 13 Demonstration at 2005 World Exhibition

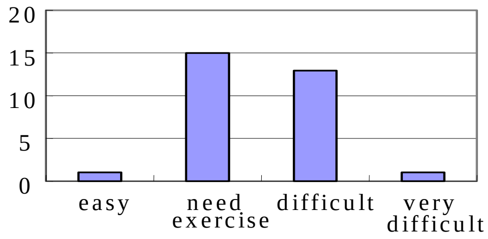


Fig.14 User evaluation of manipulability

most of the users evaluated the HIRO II to be very attractive and have high potential as a 5 fingered haptic interface.

5. Conclusion

A new developed five-fingered haptic interface robot named HIRO II is presented. The haptic interface was designed to be completely safe, and to be similar to the human upper limb in shape and motion ability. The interface is placed opposite to the human hand to free the operator from its weight, and is completely safe to protect the operator from its malfunctions. Designs of haptic hand and haptic arm have been presented. A redundant force control of the haptic interface have been evaluated experimentally. Moreover, the operability has been evaluated in the prototype robot exhibition at 2005 World Exhibition. These show that the HIRO II has high potential for multi-fingered haptic interface.

The interface will be utilized in a wide range of applications as a master or a slave in real and virtual environments. The future works are directed to the implementation of the interface in various applications.

Acknowledgment

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