Five-Fingered Haptic Interface Robot: HIRO III

Takahiro Endo, Member, IEEE, Haruhisa Kawasaki, Member, IEEE, Tetsuya Mouri, Yasuhiro Ishigure, Hisayuki Shimomura, Masato Matsumura, and Kazumi Koketsu

Abstract—This paper presents the design and characteristics of a five-fingered haptic interface robot named HIRO III. The aim of the development of HIRO III is to provide a high-precision three-directional force at the five human fingertips. HIRO III consists of a 15-degrees-of-freedom (DOF) haptic hand, a 6-DOF interface arm, and a control system. The haptic interface, which consists of a robot arm and hand, can be used in a large workspace and can provide multipoint contact between the user and a virtual environment. However, the following problems peculiar to a multi-DOF robot have arisen: a large amount of friction, a backlash, and the presence of many wires for many motors and sensors. To solve these problems, a new mechanism and a wire-saving control system have been designed and developed. Furthermore, several experiments have been carried out to investigate the performance of HIRO III. These results show the high-precision force display and great potential of HIRO III.

Index Terms—Design, Haptic I/O, Interfaces, Virtual reality

1 INTRODUCTION

Multi-fingered haptic interfaces that allow multipoint contact between users and a virtual environment have greater potential for various applications than do single-point haptic interfaces. The multipoint interaction allows a user to perform natural actions such as grasping, manipulation, and exploration of virtual objects, and such interaction will dramatically increase the believability of the haptic experience [1-3]. In performing activities in our daily lives, we usually use multiple fingers and grasp and manipulate objects with dexterity. Furthermore, the exploration of an object is affected by the number of fingers used, and exploration with multiple fingers is more effective than exploration with a single finger [4-6]. Thus, it is important to be able to exert force at multiple fingertips in order to generate a sensation that is highly realistic to human beings. In addition, since we are familiar with activities that involve multiple fingers, the multi-fingered haptic interface can be used naturally and without extensive familiarization. Based on these considerations, the development of a multi-fingered haptic interface has been eagerly anticipated and is expected to further haptics in virtual environments.

Although the development of a multi-fingered haptic interface continues to pose design and technical challenges [7, 8], several multi-fingered haptic interfaces have been pursued aggressively [2, 3, 5, 7-21] because of their potential effectiveness and usefulness. The current multi-fingered haptic interfaces can be divided into two groups: grounded-type haptic interfaces [2, 3, 5, 9-21] and ungrounded-type (exoskeleton-type) haptic interfaces [7, 22-25]. The exoskeleton-type haptic interface has a large workspace, but with this interface it is difficult to present three-directional forces or the weight of virtual objects through the fingertips because the hand mechanism is mounted on the back of a human hand, and the exerted force is only a one-directional force. For example, when the haptic interface generates force by using a wire, the force applied to the operator is only exerted in the direction that the wire pulls. Thus, it is difficult to present a delicate force or the weight of virtual objects. As exceptions, A. Frisoli et al. [7] and T. Koyama et al. [25] have developed exoskeleton-type haptic interfaces that can present three-directional force at human fingertips. They used a serial link mechanism in the design of the haptic interface and were able to present a three-directional force at two or three of the user’s fingertips. However, the mechanism is mounted on the user’s hand, and thus it is difficult to present the weight of virtual objects, and it is difficult to use the haptic interface for a long time because of its weight [3, 26].

In contrast, the grounded-type haptic interface generally has a fairly small workspace compared with the ungrounded-type haptic interface. However, a grounded-type haptic interface consisting of an arm and fingertips can be used in a large workspace [2, 3, 16-21]. F. Barbagni et al. [2] and Z. Najdovski et al. [3] have developed a multi-fingered haptic interface that consists of an arm and a gripper at the end of the arm. Unlike the haptic interface which achieves multipoint interaction by combining two or three haptic devices in parallel [13-15], the haptic interface [2, 3] can be used throughout a large workspace. However the gripper is specialized for the purpose of grasping. So the interface allows the user to grasp a virtu-
The five-fingered haptic interface robot, HIRO III, consists of a five-fingered haptic hand and an interface arm, as shown in Figure 1. HIRO III can present a three-directional force at five human fingertips. It is placed opposite a human hand, and the haptic fingertips are connected to the human fingertips through passive spherical permanent magnet joints. This section presents the mechanical design of HIRO III.

2.1 Haptic Hand

The haptic hand is constructed of five haptic fingers and a handbase. The structure of the haptic hand is shown in Figure 2, and its specifications are shown in Table 1. Each finger has 3 joints, allowing 3 DOF. The 1st joint relative to the handbase allows abduction/adduction, while the 2nd and 3rd joints allow flexion/extension. All joints are driven by DC motors with gear and rotary encoders, where the gear consists of the gearhead of the motor and the gear of the transmission mechanism. Another important issue is the installation of force sensors. To read the finger loading forces, a previously developed three-

Fig. 1. Five-fingered haptic interface robot: HIRO III. A user connects his/her five fingertips to HIRO III through passive spherical permanent magnet joints.

al object via a simple open-close movement, but the operator cannot grasp/manipulate an arbitrarily shaped virtual object with dexterity. Furthermore, most of the above haptic interfaces consist of a hand-exoskeleton-and-arm [16-18] or a hand-and-arm-exoskeleton [19, 20] system, and thus the interfaces have the same problems as the exoskeleton type haptic interface. As a minority case, Y. Yokokohji et al. [21] proposed the concept of an encountered-type haptic interface for human grasping. Although this device would be an ideal haptic interface, it has proven to be difficult to achieve using the present technology.

We concluded that the desirable attributes for a haptic interface include the following: the haptic interface must be safe, function in a wide space, and present not only three-directional force at the contact points but also the weights of virtual objects. In addition, it should neither cause an oppressive feeling when attached to the user’s hand, nor should it represent its own weight. To meet these requirements, we have developed multi-fingered haptic interface robots that are placed opposite a human hand, known as HIRO [27] and HIRO II [28]. Most haptic devices have a low reduction ratio, which permits impedance control without the use of a force sensor. However, this requires a large mechanism and entails difficulty in construction. Therefore, HIRO and HIRO II have high reduction mechanisms and require a force sensor on each haptic fingertip. Although the haptic interface with a robot hand allows multipoint interaction, the robot hand is a multi-DOF device, which means that many motors, sensors, and amplifiers are needed. Because of the many wires required for the motors and sensors, it is difficult to miniaturize the control system and to operate the interface smoothly.

To provide high-precision force representation and to meet the functionality requirements, including light weight, low friction, low backlash, compactness, and so on [29], we consider the following attributes to be important: 1) a mechanical design that reduces friction and backlash, 2) a wire-saving control system, and 3) high-precision three-axis force sensors. With these concerns in mind, we have newly developed a five-fingered haptic interface robot, HIRO III. It consists of a haptic hand with five haptic fingertips, an interface arm, and a control system. To satisfy item 1), a new mechanism for the haptic hand and interface arm was designed that has accomplished the following: a reduction of the static friction, greater compactness, an improved layout of the joints, and a connection method for the touch between the human fingertips and the haptic fingertips. To reduce the number of wires and to increase the compactness of the haptic interface, we have newly developed a wire-saving control system, which consists of an interface FPGA circuit, a force sensor amplifier circuit, and a motor amplifier circuit. To present the force at the five human fingertips, HIRO III requires 21 motors, 21 encoders, and 5 force sensors. Because of this, the communication cables between HIRO III and its control PC include a total of 212 wires. However, our new wire-saving control system was installed in HIRO III. The force sensor, encoder, and motor signals are inputted into the wire-saving system and communicate to the control PC on a LAN. Therefore, we were able to reduce the number of wires from 212 to 20. Thus, item 2) has been satisfied. We previously developed the wire-saving control system and the high-precision three-axis force sensor, which correspond to item 3), for HIRO II [30]. However, the interface FPGA circuit and the motor driver consist of several circuits and thus are not compact. Furthermore, we were not able to obtain a high-precision force presentation at the five human fingertips in the experiments with HIRO II.

In this paper, we describe the development of a five-fingered haptic interface robot, HIRO III, which was designed in accordance with the above three items, and our experimental investigation of its performance. This paper is organized as follows: In the next section we introduce the mechanical design of HIRO III. Section 3 presents the newly developed control system for HIRO III. The experimental results described in Section 4 demonstrate the high potential of HIRO III. Finally, Section 5 presents our conclusions.
axis force sensor [30] is installed in the 2nd link of each finger.

2.1.1 Haptic fingers

The haptic fingers of HIRO III are superior to those of HIRO II+ in the following ways: 1) the static friction at the 1st and 2nd joints of each finger has been reduced; and 2) the connecting position between the human fingertip and the haptic fingertip has been changed. The haptic finger of HIRO II+, which is shown in Figure 3, was designed based on an anthropomorphic robot hand [31]. As stated above, each finger has 3 joints, allowing 3 DOF. To orthogonalize the 1st joint axis to the 2nd joint axis, an asymmetric differential gear was adopted. This increased the compactness of the mechanism but provoked a large amount of friction and a backlash, and it required a great deal of maintenance. Even if the differential gear was useful for the robot hand, it had crucial disadvantages for the haptic interface. Therefore, we developed new haptic fingers in which each axis is independently driven without the differential gear. To realize an operation similar to that of HIRO II+ without using the differential gear, we placed the motors on the shell side of the hand palm, as shown in Figure 4. The specifications of the motors are listed in Table 2.

To investigate the effectiveness of the mechanism, we measured the backlash and the static friction at the joints. To investigate the backlash, we measured the free running angle of the joint. Note that all links were fixed with a jig. The free running angle of clockwise (CW) and counterclockwise (CCW) rotation was alternatively measured five times, and the average value was calculated. To assess the static friction torque, we measured the torque where the joint began to move. The static friction torque of CW and CCW rotation was alternatively measured five times, and we obtained the average value. Table 3 shows the measurement results. In terms of the backlash, there was no large difference between the haptic fingers of HIRO II+ and those of HIRO III. For the haptic fingers of HIRO III, we used the same motor and motor gearhead as in the haptic fingers of HIRO II+, and thus the obtained backlash is the backlash of the motor gearhead, which would be difficult to improve by altering only the transmission mechanism. On the other hand, the static friction of the 1st and 2nd joints was reduced by 50% and 45%, respectively. In HIRO III, we eliminated the asymmetric differential gear and developed a new mechanism in which each axis is independently driven. This reduced the number of stages of the gear mechanism and reduced that weight of the joints. These features combine to reduce the friction at the 1st and 2nd joints. Here note that there is no change to the transmission mechanism at the 3rd joint. Therefore, there is no large difference at the 3rd joint.

We also improved the connecting position between the human and haptic fingertips. In particular, we changed

---

**Table 1**

<table>
<thead>
<tr>
<th>Hand</th>
<th>Num. of fingers</th>
<th>Degrees of freedom</th>
<th>Weight including wire-saving control system</th>
<th>Nominal torque [mNm]</th>
<th>Nominal current [A]</th>
<th>Gear ratio(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingers</td>
<td>5</td>
<td>15 [DOF]</td>
<td>under 0.78 [kg]</td>
<td>maxon DC motor RE10 256105</td>
<td>1.54</td>
<td>0.176</td>
</tr>
</tbody>
</table>

(*) The gear consists of the gearhead of the motor and the gear of the transmission mechanism.

**Table 2**

<table>
<thead>
<tr>
<th>Joint</th>
<th>Part number</th>
<th>Nominal torque [mNm]</th>
<th>Nominal current [A]</th>
<th>Gear ratio(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>maxon DC motor RE10 256105</td>
<td>1.54</td>
<td>0.176</td>
<td>768 / 554.7 / 140.8</td>
</tr>
<tr>
<td>2nd</td>
<td>3rd</td>
<td>3rd</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3**

<table>
<thead>
<tr>
<th>Backlash [deg]</th>
<th>Joint</th>
<th>HIRO II</th>
<th>HIRO III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st / 2nd / 3rd</td>
<td>0.49 / 1.07 / 0.72</td>
<td>0.47 / 0.94 / 0.75</td>
<td></td>
</tr>
<tr>
<td>Static friction torque [mNm]</td>
<td>1st / 2nd / 3rd</td>
<td>0.28 / 0.31 / 0.07</td>
<td>0.14 / 0.14 / 0.08</td>
</tr>
</tbody>
</table>
the fingertip form of the thumb and pinky, as shown in Figure 5. To manipulate the haptic interface, the user wears a finger holder (Figure 5(c)) on each of his/her fingertips. The finger holder has a sphere which, when attached to the permanent magnet at the fingertip, forms a passive spherical joint. The role of the passive spherical joint attached to the permanent magnet is to adjust the differences between the orientations of the human and haptic fingers and to ensure that the operator can remove his/her fingers from the haptic interface if it malfunctions. The permanent magnet at the fingertip is in a hole, as shown in Figures 5(a) and (b). The entire fingertip of HIRO II is shown in Figure 5(b). However, when a user performs natural actions such as grasping, the thumb and pinky often move outside the workspace. By diagonally moving the contact point of the thumb and pinky, we solved this problem. In other words, we moved the contact point so that it is oriented 45 deg from horizontal (see Figure 6). We then obtained a working space of the finger holder for the thumb and pinky fingertips with a pitch axis of -33~102 deg and a yaw axis of -78~78 deg. Here, the working space of the finger holder for the other fingertips has a pitch axis of -80~72 deg and a yaw axis of -78~78 deg. As a guide, we show a closeup photo of the connection between the user’s hand and the interface in Figure 6(c).

### 2.1.2. Haptic finger layout

For the finger layout, we duplicated the method used in HIRO II*, which optimized the design performance index (see [28] for details). In HIRO II*, an asymmetric differential gear was adopted, and thus the 1st and 2nd motors of the fingers other than the thumb were stored inside the handbase. For HIRO III, we used the same finger layout as in HIRO II* with the 1st and 2nd motors being placed at the shell side of the handbase, as shown in Figure 4. Therefore, we were able to create space inside the handbase, where we installed the wire-saving control system.

### 2.2 Interface Arm

An overview of the interface arm is shown in Figure 7. The arm joint, including the 1st, 2nd, and 3rd joints, is actuated by an AC motor. The wrist joint, including the 4th, 5th, and 6th joints, is actuated by a DC motor. The interface arm, therefore, has 6 joints allowing 6 DOF. Tables 4 and 5 show the specifications of the interface arm joints. We used a motor with a brake for joints 2 and 3 in order to hold the arm in position after the power is turned off. Since we consider the performance and size of the motor as the selection criteria, and we were only able to find a suitable AC motor, we chose an AC motor for joints 2 and 3, and we used the same AC motor for joint 1 to create uniformity with joints 2 and 3. The main improvements of the interface arm of HIRO III over that of HIRO II* are the following: 1) compactness, 2) a change in the layout of the 1st joint, 3) a reduction of
Fig. 8. Structure of the interface arm of HIRO II⁺.

<table>
<thead>
<tr>
<th>Joint</th>
<th>HIRO II</th>
<th>HIRO III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st / 2nd / 3rd</td>
<td>1.66 / 1.18 / 4.36</td>
<td>2.97 / 2.00 / 0.88</td>
</tr>
<tr>
<td>4th / 5th / 6th</td>
<td>5.52 / 3.68 / 2.98</td>
<td>4.61 / 4.72 / 3.00</td>
</tr>
</tbody>
</table>

Table 6

BACKLASH AND FRICTION TORQUE OF THE INTERFACE ARM.

the static friction at the joints, and 4) light weight. Regarding item 1, the interface arm of HIRO II⁺ was designed to be as similar as possible to the human arm, as shown in Figure 8. This design resulted to a large workspace, but a smaller workspace is sufficient to perform many tasks on a desktop. Thus, we designed the arm length of HIRO III to be shorter than that of HIRO II⁺. On the other hand, HIRO II⁺ has a 2-DOF shoulder joint, which allowed for shoulder adduction/abduction (1st joint) and shoulder flexion/extension (2nd joint). When an operator uses HIRO II⁺ and pushes the interface, its elbow part collides with the base. Therefore, we changed the layout of the 1st joint from shoulder adduction/abduction to shoulder radial/lateral rotation, which corresponds to item 2. We also made an offset between the 1st and 2nd joints, as shown in Figure 7. This helps to compensate for the reduced workspace. We note that HIRO III has no shoulder adduction/abduction; these motions are covered by the 4th joint. Regarding item 3, we show the measurement results for the backlash and the static friction at the joints in Table 6. The method of measuring these values is the same as in the case of the haptic finger. Table 6 indicates that there was a large improvement in the static friction. The 5th and 6th joints stopped the use of the differential gear, and these joints work independently. Thus we reduced the number of stages of the gear mechanism and saved weight in the joints, which helped to reduce the static friction. In particular, the transmission mechanism of the 5th joint was changed from the gear to the timing belt, and this change seems to have made a great improvement in the static friction. We realized a similar improvement by changing the transmission of the 4th joint to the timing belt as well. We noted that the backlash of the 6th joint was greater, because the transmission mechanism of the 6th joint was stopped, and the 6th joint axis was tied directly to the gearhead of the motor. We suspect that the backlash was due to the motor’s gearhead. For the 3rd joint, although there was no change in the number of stages of the gear, we believe that good performance was obtained as a result of the compactness and reduction of the weight of the interface arm. Like the 6th joint, the 2nd joint axis was tied directly to the gearhead of the motor, and this influence seems to be reflected in the backlash. Since we changed the layout of the 1st joint, it is impossible to make a fair comparison of the 1st joint of HIRO III and the 1st joint of HIRO II⁺.

As a result of addressing items 1) to 3), the weight of the interface arm was reduced to 3 kg, which is 43% of the weight of the interface arm of HIRO II⁺; and item 4) was achieved. In the root of the interface arm, we created a box, and in it we installed the wire-saving control system for the interface arm.

### 3 Control System of HIRO III

To present the force at the five human fingertips, we installed 15 DC motors and 5 force sensors in the haptic hand of HIRO II⁺. As a result, the communication cable between the PC and the haptic hand consists of 60 wires for the 15 encoders, 30 wires for the 15 motors, and 40 wires for the 5 force sensors. In addition, the interface arm of HIRO II⁺ has 6 motors and 6 origin-seeking sensors, and the communication cables between the arm and the PC include 48 wires for the 6 encoders, 30 wires for the 6 motors, and 24 wires for the 6 origin-seeking sensors. Therefore, the total number of wires between the haptic interface and the control PC is 202. These wires greatly obstruct the smooth movement of the haptic interface. For example, the joint and the projection portion of the mechanism can become caught in the wires, and the external force exerted by the wires affects the control of the haptic interface. Furthermore, the amplifiers of the force sensors and motors are stored under the haptic interface. Although the force sensor amplifiers and motor amplifiers are not large, many amplifiers are needed, and their combined size is large. Thus, to solve these problems, we have developed compact wire-saving control systems for the haptic hand and for the interface arm.

#### 3.1 Control system for the haptic hand

The wire-saving control system for the haptic hand consists of the interface FPGA circuit, the force sensor amplifier circuit, and the motor amplifier circuit. Figure 9 shows a block diagram of the communication among these circuits. In the FPGA, the VHDL language was used to create a counter driver to count the up/down pulses from the motor amplifier circuit, a PWM driver to provide the PWM outputs of 15 motors, and a sensor driver to read the digital values of the 5 force sensors and to provide the zero adjustment value of the 5 force sensors. The FPGA sends the sensors’ signals to the control PC each time the PC sends the commands. When the PC sends the zero-adjustment signals of the force sensors, the FPGA sends digital signals corresponding to the zero-adjustment signals to the D/A converter in the force sensor amplifier circuit. In addition, the FPGA sends a PWM signal to the motor amplifier circuit when it receives the duty ratio signal from the control PC.

The main functions of the motor amplifier circuit are amplifying the 15-ch PWM signals from the FPGA circuit...
the force sensor is suitable for the measurement of dynamic phenomena because the amount of displacement is extremely small. Figure 11 shows the sensor structure of the 3-axis force sensor. For the acting axis force, the strain gauges are installed at the surface of the spot where the stress of the sensor element reaches a maximum, and the force is detected as a change in electrical resistance. The total number of strain gauges is 16: \( x_1 \sim x_4, y_1 \sim y_4, \text{and} \ z_1 \sim z_8. \)

| TABLE 7  |
|  |
|  |
| **SPECIFICATIONS OF THE FORCE SENSOR.** |
| **Rated capacity** | 5 [N] |
| **Rated output (X-, Y-, Z-direction)** | ±0.3, ±0.3, ±0.1 [mV/V] |
| **Safe overload** | 400 [%] |
| **Nonlinearity, hysteresis** | ≤ 1.0 [%RO] |
| **Repeatability** | ≤ 1.0 [%RO] |
| **Size / Weight** | \( \phi 14 \times H27 \) [mm] / 12.8 [g] |

For the forces in the X- and Y-directions, bending strains of \( x_1 \sim x_4 \) and \( y_1 \sim y_4 \), respectively, are detected. Further, shear strains of \( z_1 \sim z_8 \) are detected for the force in the Z-direction. The specifications of the 3-axis force sensor are shown in Table 7.

The wire-saving control system for the haptic hand is installed in the space inside the handbase, as shown in Figure 12. The force sensor, encoder, and motor signals are input into the control system and communicate with the control PC by an Ethernet connection. This allows us to reduce the number of wires between the haptic hand and converting the level of the 15-ch encoder signals. The signal flow of the motor amplifier circuit is shown in Figure 9 (b). Figure 9 (c) shows the signal flow of the force sensor amplifier circuit. With these measures, we believe we have achieved a high-precision force measurement. Furthermore, we installed a 12-bit D/A converter in the circuit because of the zero adjustment of the force sensors. Figure 10 shows the 3-axis force sensor, which was developed previously [30]. The sensor measures the 3-axis forces, \( F_x, F_y, \) and \( F_z \) at the haptic fingertip. The force sensor is installed in the 2nd link of each haptic finger and is connected to the sensor amplifier circuit. The force sensor must be small enough to install at the haptic fingertip. We set the following goals for the force sensor: 1) a low load can be measured; 2) its outside diameter is 14 mm; and 3) the interference between axis forces in the sensor element is minimal. By using the strain gauge in the pressure port of the sensor element, the force sensor measures the force from the deformation of the metal beam. The reasons for using the strain gauge are: 1) the sensor has better linearity; 2) the effect of the temperature change is small; and 3) the force sensor is suitable for the measurement of dynamic phenomena because the amount of displacement is extremely small. Figure 11 shows the sensor structure of the 3-axis force sensor. For the acting axis force, the strain gauges are installed at the surface of the spot where the stress of the sensor element reaches a maximum, and the force is detected as a change in electrical resistance. The total number of strain gauges is 16: \( x_1 \sim x_4, y_1 \sim y_4, \text{and} \ z_1 \sim z_8. \)
and the control PC from 115 to 10, including 8 wires for the Ethernet and 2 wires for the power supply. The communication is fulfilled by UDP/IP and is a command-and-response type of communication. Since the retransmission processing is built into the control PC, the communication is reliable. We carried out several experiments, as described in Section 4. In these experiments, communication (sending and receiving) including latency was accomplished in 0.3 ms, and we were able to control HIRO III at a sufficient control rate (1 kHz).

### 3.2 Control System for the Interface Arm

The wire-saving control system for the interface arm consists of the interface FPGA circuit and the motor amplifier circuit. Figure 13 shows a block diagram of the communication between these circuits. The main differences from the hand control system are the following: 1) there is no force sensor amplifier circuit; and 2) a DIO driver was prepared in FPGA for the brakes of the motors and the origin-seeking sensors. The functions of PWM output, up/down count, and communication are the same as in the hand control system. Regarding the reset functions, in the interface arm, the 2nd and 3rd motors have brake systems that are connected to the motor amplifier circuit. The FPGA sends the on-off signal based on commands from the control PC, and the voltage conversion of the on-off signal is carried out in an FET (Field Effect Transistor) on the motor amplifier circuit. This on-off signal controls the brake. We used a photointerrupter as an origin-seeking sensor. The output of this sensor is input into the FET, and the on-off signal is created and input into the FPGA circuit. The FPGA sends this on-off signal to the control PC each time the PC sends the commands.

The wire-saving control system for the arm is installed in the space inside the box at the root of the interface arm, as shown in Figure 14, and this system allows us to reduce the number of wires between the interface arm and

---

### Table 8

<table>
<thead>
<tr>
<th>Specifications: Wire-Saving Control System for the Haptic Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interface FPGA Circuit</strong></td>
</tr>
<tr>
<td>Size: W70·D70·H1.6 [mm]</td>
</tr>
<tr>
<td>FPGA Type: Xilinx Corp., Spartan3E (XC500E)</td>
</tr>
<tr>
<td>Clock frequency: 100 [MHz]</td>
</tr>
<tr>
<td>Ethernet Communication: 100Base-TX, protocol: UDP</td>
</tr>
<tr>
<td><strong>Motor amplifier circuit</strong></td>
</tr>
<tr>
<td>Size: W70·D70·H4 [mm] / 15</td>
</tr>
<tr>
<td>Motor input signal form: PWM</td>
</tr>
<tr>
<td><strong>Force sensor amplifier circuit</strong></td>
</tr>
<tr>
<td>Size: W70·D70·H5 [mm] / 15</td>
</tr>
<tr>
<td>Amp output: Differential amp, Scale factor 2.5</td>
</tr>
<tr>
<td>ADC: Type: Resolution ADS1258 (Texas Instruments Inc.) / 24 [bit]</td>
</tr>
<tr>
<td>DAC: Type: Resolution AD5328 (Analog Devices Inc.) / 12 [bit]</td>
</tr>
</tbody>
</table>

---

### Table 9

<table>
<thead>
<tr>
<th>Specifications: Wire-Saving Control System for the Interface Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interface FPGA Circuit</strong></td>
</tr>
<tr>
<td>Size: W70·D70·H15 [mm]</td>
</tr>
<tr>
<td>FPGA Type: Xilinx Corp., Spartan3E (XC500E)</td>
</tr>
<tr>
<td>Clock frequency: 100 [MHz]</td>
</tr>
<tr>
<td>Ethernet Communication: 100 Base-TX, protocol: UDP</td>
</tr>
<tr>
<td><strong>Motor Amplifier Circuit</strong></td>
</tr>
<tr>
<td>Size: W170·D85·H17 [mm] / 6</td>
</tr>
<tr>
<td>Motor input signal form: PWM</td>
</tr>
</tbody>
</table>

---

Fig. 13. Block diagram of the wire-saving control system for the Interface arm.

Fig. 14. Interface arm in which the wire-saving control system is installed inside the root.

Fig. 15. Control System of HIRO III.
the control PC from 90 to 10 (8 wires for the Ethernet and 2 wires for the power supply). Table 9 shows the specifications of the wire-saving control system for the interface arm.

By developing this compact wire-saving control system, we were able to reduce the number of wires between HI-RO III and the control PC from 212 to 20, to increase the unit’s compactness, and to improve the transportability of the total interface. Figure 15 shows the control system of HIRO III.

4 EXPERIMENT

To evaluate HIRO III, we carried out several experiments. As the control law, we used the manipulability-optimized control [18]. This is a mixed control method consisting of a force-feedback control and an arm position control intended to maximize the control performance index (3). The force control of the haptic finger is given by

\[ \tau_f(t) = K J^T_f F_f(t) + K J^T_f \int_0^t F_f(s) ds + J^T_f F_f - K \dot{q}_f(t), \]

where \( \tau_f = [\tau_1, \ldots, \tau_6]^T \in \mathbb{R}^6 \) is a joint torque vector of the haptic finger, \( J_f \) is a Jacobian, \( F_f = [F_{f_1}, \ldots, F_{f_6}] \in \mathbb{R}^6 \) is a force vector whose sub vector is the force vector at the fingertip, \( F_t = [F_{t_1}, \ldots, F_{t_6}] \in \mathbb{R}^6 \) is the desired force, \( F_f = F_{f_a} - F_f, \) and \( q_f = [q_{f_1}, \ldots, q_{f_6}] \in \mathbb{R}^6 \) is a joint angle vector of the haptic finger. Furthermore, \( K \) is the positive feedback gain matrix. Here, the fourth term is the velocity feedback to employ the active damping. On the other hand, the control of the interface arm is given by the following PD (proportional and derivative) control with gravitational and external force compensators:

\[ \tau_q(t) = K_J (q_{a_d} - q_a) + K_J (q_{a_d} - q_a) \]

\[ + g_s (q_a) + J^T_q \left( \sum_{i=1}^6 F_{a_i} - J^T_{a_d} \left( \sum_{i=1}^6 (p_i - p_{a_b}) \times F_{a_i} \right) \right), \]

where \( q_a \in \mathbb{R}^6 \) is the arm joint angle vector, \( q_{a_d} \in \mathbb{R}^6 \) is the desired arm joint angle vector, which is to be determined, \( \tau_q \in \mathbb{R}^6 \) is the interface arm joint torque, \( K_Q \) is the gravitational compensator term, \( J_q \) is a Jacobian, \( p_i \in \mathbb{R}^6 \) is the i-th fingertip position vector, and \( p_{a_b} \in \mathbb{R}^6 \) is the tip of the interface arm. Here note that the desired arm joint angle vector \( q_{a_d} \) is defined to maximize the following control index (3) under a constraint condition in which the five haptic fingertip positions are fixed to the operator fingertip positions:

\[ \text{CPI} = \sum_{i=1}^5 \left( \alpha_i W_i + \beta_i P_i + Q_i \right), \]

\[ W_i = (\text{det}(J^T_{a_i} J_{a_i}))^2, \]

\[ Q_i = -\frac{1}{2} (q_{a_d} - q_a) J^T_f F_{f_a} - q_{a_d} J^T_f F_{f_a}, \]

\[ P_i = \sum_{j=1}^6 \gamma_i \left( \exp(-\mu(q_{a_j} - a_{g_j})) + \exp(\mu(q_{a_j} - b_{g_j})) \right), \]

where \( \alpha_i, \beta_i \) are weighting coefficients, \( W_i \) is a manipulability measure of the i-th finger, \( P_i \) is a penalty function to keep the joint angle within the movement range, \( \gamma_i \) is the weighting coefficient, \( \mu \) is the parameter to adjust an exponential function, \( a_{g_j} \) and \( b_{g_j} \) are the lower and upper limits of the j-th joint angle of the i-th finger, \( Q_i \) is the penalty function to prevent a large change of the arm angle, and \( F > 0 \) is a weighting matrix. Here, in the control, a finger/arm that reaches the limit of the movable range is switched to a position control to keep the joint angle in the movable range, and the rest joints of the fingers/arm are controlled by (1)/(2). After returning to within the movable range, the control is switched back again to (1)/(2). Details of the control law have been shown in [18].

In the above control, the feedback gain is constant. When a user manipulates the haptic interface in free space, the user feels the inertia and friction of the interface, and therefore a high-gain feedback is desired. On the other hand, when a user uses the haptic interface in the constraint space, namely when the user contacts a virtual object, the high-gain feedback creates a vibrating response, and a low-gain feedback is desired. Therefore, in our experiments, we improved the force control of the haptic fingers include with non-constant gain. The controller uses a high gain when the desired force is zero and a low gain when the desired force is not zero. For the experiment, the control PC used a real-time OS (ART-Linux) to guarantee a 1 ms sampling time.

4.1 Experiment 1

In the control of HIRO III, the force applied to the user’s fingertips is provided by the force control of the haptic fingers. Therefore, to assess the basic force exertion performance, we considered the force exertion performance of HIRO III without using the interface arm in experiment 1. First we considered the displayable stiffness of HIRO III. To assess it, we carried out a contact experiment involving a virtual wall [32]. In this experiment, a user connected his/her index finger to the haptic index finger of HIRO III. We made a virtual wall by using a spring-damper model, and the desired force at the haptic finger was set to \( F_{f_a} = K x_s + B x_s \), where \( x_s \) is the penetration depth of the 2nd haptic finger into the virtual wall, and \( K \) and \( D \) are the stiffness and the damping coefficient of the virtual wall, respectively. Within view of the user, the virtual wall was set to a location about 2 mm away in the direction of the HIRO III (the y-axis direction in Figure 4). Six people in their twenties participated in the experiment. The experimental procedure was as follows: 1) a damping coefficient, \( D_i \) was set; 2) the participant connected his/her index finger to HIRO III; 3) the participant enlarged the stiffness coefficient \( K \) from 0 N/m at intervals of 50 N/m; and the participant touched the virtual wall and moved his/her fingertips on the surface of the virtual wall in every case. If the participant felt the vibration, the
stiffness coefficient, $K$, before one-step was the maximum displayable stiffness coefficient at the damping coefficient, which was set in 1). Then the participant returned to step 1) and set the damping coefficient $D$ to the next value. Six participants’ displayable stiffnesses are shown in Figure 16. In the figure, the region formed by the $D$-axis, the $K$-axis, and each participant’s curve is the region where the corresponding participant could feel the smooth surface of the virtual wall without any vibrations. We observed no large differences among the different subjects’ curves, and the maximum displayable stiffness was about 5 kN/m.

In association with the above stiffness response, we also considered the frequency response of the haptic index finger. As the input of the force control, we selected the following sinusoidal function: $F_0=[0, \sin(\omega t), 0]^T$, where $\omega=2\pi f$ is the angular frequency and $f$ is the frequency. As the output, we selected the $Y$-axis force of the haptic index fingertip. In the measurement, the operator connected his index finger to the haptic index finger, and the subject’s finger was fixed to a bar so that it could not move during the measurement. We considered frequencies $f$ Hz from 0 to 10, and we measured the force responses at each $f$ three times. The mean value at each $f$ is shown in Figure 17. This figure shows only the $Y$-axis frequency response, but we also measured the $X$- and $Z$-axis responses, which were almost the same as the $Y$-axis result. The bandwidth of the force control was about 8 Hz, and we found that HIRO III could track high-speed motions of the operator such as tapping.

Finally, we considered the force responses of the haptic index finger using the same experimental environment as in the contact experiment described above. In this case, the participant connected his index finger to the haptic index finger and pushed the virtual wall several times. The stiffness coefficient $K$ and the damping coefficient $D$ of the virtual wall were set at $K=3$ kN/m and $D=50$ Ns/m. Figure 18 (a) shows the three-axis force responses of the haptic index finger. The virtual wall was set at a location about 2 mm away in the $Y$-axis direction, and thus the desired force was set at $F_d=[0, K_0, D_0, 0]^T$. The average force errors of the $X$-, $Y$-, and $Z$-axes were 0.07, 0.16, and 0.08 N, respectively, and the total average force error was 0.10 N. Since human fingers can only sense force variations as small as 0.5 N [33], these force errors are sufficiently small. Figure 18 (b) shows the $Y$-axis fingertip position of the haptic index finger. The figure also shows the position of the virtual wall. From this figure, we can confirm that the participant moved his finger to the virtual wall and then pushed the virtual wall. Note that the participant kept touching the virtual wall until the moment the measurement was finished. In addition, we also considered the force response of the haptic index finger in free space. The desired force of the index finger was set at $F_{e_i}=[0,0,0]^T$. The operator connected his index finger to the haptic index finger and then shuttled his finger along the $Y$-axis. The amplitude of the shuttle was 2 cm. The average force errors of the $X$-, $Y$-, and $Z$-axes were 0.04, 0.06, and 0.05 N, respectively, and the total average value was 0.05 N. Compared with the virtual wall experiment, in which the desired force was not zero, the force errors of all axes were small.

4.2 Experiment 2

Next, we considered the motion performance of HIRO III using the haptic hand and the interface arm. The operator’s five fingers were connected to HIRO III, and the operator manipulated HIRO III in free space so as to draw a triangle in VR space, as shown in Figure 19. Here note that the operator was not instructed to track a virtual triangular target, but was allowed to execute any size of triangular trajectory that he or she desired.

Figure 20 shows the responses of HIRO III in free space. In the figure, (a) shows the responses of the five fingertip positions of HIRO III, while (b) shows the average force errors of the middle and pinky fingertips of HIRO III. For the $X$- and $Z$-axes in (a), see the axes in Figure 21. Since we were considering the manipulation of HIRO III in free space, the desired forces at the five fingertips were set to zero. However, the responses of the fingertip forces show a slight force error. The average force errors of each finger were 0.093 N for the thumb, 0.091 N for the index finger, 0.095 N for the middle finger, 0.072 N for the ring finger, and 0.070 N for the pinky, and the total average force er-
observation could be made about experiment 3. Note that, because of safety constraints, our current research did not target high-speed motion. In the future, the performance (force error) during high-speed motion must be improved so that it is similar to that achieved in slow motion. On the other hand, the connection between the operator and HIRO III is accomplished by permanent magnets. The breaks in these connections depend not on the manipulation speed of HIRO III but on the force with which the operator pulls his/her fingers from HIRO III. Currently the permanent magnet connection breaks if the operator pulls his/her finger with a force of about 4.3 N.

4.3 Experiment 3

Finally, we considered the manipulation ability of HIRO III in a constraint space using the haptic hand and the interface arm. In the experiment, the operator’s five fingers were connected to the haptic interface, and the operator moved his five fingertips as shown in Figure 22. The operating procedure was as follows: 1) the operator approached the virtual cubic object; 2) the operator grasped the object; 3) the operator lifted the object; and 4) the operator drew a triangle while grasping the cube in the VR space.

The force displayed at the i th human fingertip (the desired force) is \( f_i = f_i^0 + f_i^1 \), where \( f_i^0 \) and \( f_i^1 \) are the constraint and the friction force of the i th fingertip, respectively. In the experiment, when the finger contacts the virtual object, we set \( f_i^0 \) and \( f_i^1 \) at each finger as the following:

\[
\begin{align*}
    f_i^0 &= k_i a_i^0 + d_i v_i^e, \\
    f_i^1 &= \frac{|\mathbf{r}_i|}{|\mathbf{r}_i| + \gamma_i t_i} f_i^e,
\end{align*}
\]

where the penetration depth vector of the i th finger into the object is decomposed to a normal direction vector \( a_i^0 \) and a frictional directional vector \( a_i^1, v_i^e \) is the relative speed between the fingertip velocity and object velocity, \( K \) is the stiffness of the object, and \( D \) is the damping coefficient of the object. Furthermore, \( d_i \) is the coefficient of static friction given by \( d_i = \frac{\eta_i}{\sqrt{|\mathbf{r}_i|^2}} \).\( \lambda_i \) is the coefficient of the dynamic frictional force, \( \gamma_i \) is the damping coefficient at the dynamic friction state, and \( t_i \) is the unit vector of the frictional force direction. In the experiment, we set \( K=300, D=1.4 \times 10^{-3}, d=1.5, \lambda_i=0.5, \) and \( \gamma_i=0 \). For the technical details, please see [35].

Figure 23 shows the responses in the constraint space. In the figure, (a) shows the response of the thumb fingertip of HIRO III. From (a), it is obvious that the operating procedure (1)-(4) was followed. Figures 23 (b) and (c) show the responses of the thumb and the pinky fingertip.
force of HIRO III, respectively. The average force errors of each finger were the following: 0.237 N for the thumb, 0.138 N for the index finger, 0.132 N for the middle finger, 0.199 N for the ring finger, and 0.129 N for the pinky. Total average force error was 0.167 N. Since the responses of the thumb and pinky had the largest and smallest force errors, respectively, we showed these fingertips’ responses in Figures 26(b) and (c). The force response of the axis with a large desired value has a larger force error than the force response of the axis with a small desired value. However, the force error is about 0.2 N, and we feel that HIRO III had good force tracking performance. On the other hand, the performance of HIRO III with the haptic hand and the interface arm is inferior to the performance of HIRO III using only the haptic hand (the result of experiment 1). This result is approximately the same in the case of manipulation in free space.

5 CONCLUSION

We have described a newly developed five-fingered haptic interface robot known as HIRO III. A new design mechanism for a haptic hand and interface arm was introduced, and the following functionality requirements of the haptic interface were achieved: a reduction of the static friction at the joint, a change in the connect position between the human and haptic fingertips to enable better grasping of a virtual object, greater compactness in size, and lighter weight. Furthermore, we have developed a compact wire-saving control system for the haptic hand and the interface arm. These systems are installed in the space inside the haptic interface. The force sensor, encoder, motor, brake for the motor, and zero-seeking sensor signals are input into the system and communicate to the main control PC on a LAN. This reduces the number of wires in the control system, increases compactness, and improves the transportability of the total interface. Finally, we carried out several experiments, the results of which showed the high-precision force presentation and the high potential of HIRO III.

Although the reduction of static friction at the joints was accomplished by changing the transmission mechanism by incorporating asymmetric differential gears, reducing the weight of the interface, and so on, we were not able to reduce the backlash at the joints. At the present stage, we consider that the motor’s gearhead has the largest influence, and changing the gearhead is one of our future tasks. In addition, the inertia of the arm influences the performance of the force control of the haptic interface in the experiments. In this paper, we did not consider compensating for the inertia of the arm, but we will need to devise a dynamic control law that compensates for the interface arm’s inertia as the next problem to be tackled. Furthermore, as an application of HIRO III, we have researched and developed bimanual haptic interface that can present three-directional force at the ten human fingertips of both hands.

ACKNOWLEDGMENTS

This paper was supported by the Ministry of Internal Affairs and Communications Strategic Information and Communications R&D Promotion Programme (SCOPE). The authors would like to thank Prof. S. Nakagawara for cooperating with the cover design of HIRO III.
REFERENCES


