actuators

MDPI

Article

Experimental Evaluation on Haptic Feedback Accuracy by Using Two Self-Made Haptic Devices and One Additional Interface in Robotic Teleoperation

Guan-Yang Liu [1,*], Yi Wang [1], Chao Huang [1], Chen Guan [1], Dong-Tao Ma [2], Zhiming Wei [2] and Xinan Qiu [2]

[1] Beihang University's Robotics Institute, Beijing 100191, China; zy2007607@buaa.edu.cn (Y.W.); 14071070@buaa.edu.cn (C.H.); guanchen@buaa.edu.cn (C.G.)
[2] Lanzhou Institute of Physics, Lanzhou 730030, China; madongtao@sina.com (D.-T.M.); castwzm@163.com (Z.W.); qiuxinan510@163.com (X.Q.)
* Correspondence: gyliu@buaa.edu.cn

Abstract: The goal of haptic feedback in robotic teleoperation is to enable users to accurately feel the interaction force measured at the slave side and precisely understand what is happening in the slave environment. The accuracy of the feedback force describing the error between the actual feedback force felt by a user at the master side and the measured interaction force at the slave side is the key performance indicator for haptic display in robotic teleoperation. In this paper, we evaluate the haptic feedback accuracy in robotic teleoperation via experimental method. A special interface iHandle and two haptic devices, iGrasp-T and iGrasp-R, designed for robotic teleoperation are developed for experimental evaluation. The device iHandle integrates a high-performance force sensor and a micro attitude and heading reference system which can be used to identify human upper limb motor abilities, such as posture maintenance and force application. When a user is asked to grasp the iHandle and maintain a fixed position and posture, the fluctuation value of hand posture is measured to be between 2 and 8 degrees. Based on the experimental results, human hand tremble as input noise sensed by the haptic device is found to be a major reason that results in the noise of output force from haptic device if the spring-damping model is used to render feedback force. Therefore, haptic rendering algorithms should be independent of hand motion information to avoid input noise from human hand to the haptic control loop in teleoperation. Moreover, the iHandle can be fixed at the end effector of haptic devices; iGrasp-T or iGrasp-R, to measure the output force/torque from iGrasp-T or iGrasp-Rand to the user. Experimental results show that the accuracy of the output force from haptic device iGrasp-T is approximately 0.92 N, and using the force sensor in the iHandle can compensate for the output force inaccuracy of device iGrasp-T to 0.1 N. Using a force sensor as the feedback link to form a closed-loop feedback force control system is an effective way to improve the accuracy of feedback force and guarantee high-fidelity of feedback forces at the master side in robotic teleoperation.

Keywords: force sensor; haptic display; human-machine interaction; teleoperation

check for updates

Citation: Liu, G.-Y.; Wang, Y.; Huang, C.; Guan, C.; Ma, D.-T.; Wei, Z.; Qiu, X. Experimental Evaluation on Haptic Feedback Accuracy by Using Two Self-Made Haptic Devices and One Additional Interface in Robotic Teleoperation. *Actuators* **2022**, *11*, 24. https://doi.org/10.3390/act11010024

Academic Editor: Daniele Leonardis

Received: 15 December 2021
Accepted: 12 January 2022
Published: 14 January 2022

1. Introduction

It is undeniable that the role of vision is fundamental and essential for obtaining information benefiting users in the successful completion of teleoperation tasks [1–3]. Furthermore, we believe that haptic display plays an indispensable role in numerous robotic teleoperations since feedback force is an important supplement to visual display to assist users in manipulating slave robots accurately, safely and effectively [4,5]. For delicate teleoperation tasks such as robot-based cell touch, bomb disposal and surgical operation, accurate feedback force is a prerequisite condition in guaranteeing a user's safe manipulation, otherwise, the consequences can be disastrous [6–8].

In haptic based teleoperation, haptic feedback plays an interactive role between the slave manipulator and its located environment to the user at the master side. The feedback force that accurately reflects the slave interaction is necessarily required for a user to feel what is happening at the slave side with clarity. The determination of feedback force accuracy is one of the basic research works that evaluate the effect and performance of haptic display in haptic based robotic teleoperation. This paper focuses on the evaluation of haptic feedback accuracy in robotic teleoperation, and whether haptic display can give users accurate feedback information that benefits them in feeling slave interactions with high- fidelity, providing the sole concern of this paper.

In teleoperation, the closed loop system in output haptic feedback to users is constituted of human operation, haptic device, various sensors in the slave robot and haptic rendering algorithm (time delay processing method) [9,10]. All of these members influence the accuracy of haptic display in teleoperation.

Human operation is sensed by haptic device as the input signal to control a slave robot to interact with the slave environment. The interaction force provided by sensors in the slave robot is measured by the input signal to render haptic feedback. For teleoperation, smooth motion signals of master haptic devices with very small fluctuations are always required to implement the slave interaction precisely and stably. Accordingly, the positioning accuracy and force application of human upper limbs are used to assess an operator's ability to complete teleoperation tasks. Therefore, the first task to identify haptic feedback accuracy in teleoperation is to determine the individual's upper limb motor ability to manipulate haptic devices.

Previous work has been focused on the evaluation of human upper limb motor ability. According to Slifkin and Newell [11], as force level increased, force variability grew exponentially. Christou [12] used a sigmoidal logistic function with respect to the level of force to describe the variability of force during continuous isometric contractions of the quadriceps femoris. Baweja [13] suggested that during constant isometric contractions, the absence of visual feedback shifted muscle activity and decreased force variability. According to the characteristics of human operation in haptic based teleoperation, we propose human hand trembling as the contrary indicator to discover the human upper limb motor ability for completion of teleoperation tasks. Human hand tremble is converted to fluctuation of the motion of haptic device's end-effector, which directly decides the quality of the motion signal used to control the slave robot. Special measurement instruments have to be developed to identify human hand tremble in robotic teleoperation.

Besides human upper limb motor ability, the performance of haptic devices are crucial for the accuracy of output force, therefore, many efforts have been made on haptic device design. Commercial haptic devices such as Omega.7, Phantom Desktop and Virtuose 6D etc. are often used as master haptic interfaces to develop haptic based teleoperation systems. Manufacturers provide specifications such as maximum output force/torque, maximum simulated stiffness, workspace and position resolution, however, the accuracy of the output force/torque are not mentioned. Pacchierotti et al. added a cutaneous device at the end-effector of a commercial haptic device and found no significant difference in a needle insertion task [14].

Moreover, researchers have focused on special devices designed for haptic based teleoperations [15,16]. A 5-DOF haptic device [17] and a 6-DOF haptic device [18] were designed using novel kinematic structures. The 10-DOF Vishard10 [19] was developed to provide a maximum feedback force of 170 N. LHIfAM was developed to provide a very large workspace for the virtual assembly of an aircraft engine. However, we cannot find articles introducing the accuracy of the output force from all aforementioned haptic devices. We believe that it is necessary to identify the accuracy of the output force from master haptic devices used in robotic teleoperation, otherwise, the effect of haptic feedback without high-fidelity simply points out whether a potential collision will occur or not.

In teleoperation, high-performance force sensors and encoders are mounted in slave robots to measure the contact and reaction between the slave robot and its located remote environment accurately [20–22]. In addition to human factors and haptic devices, haptic rendering algorithms are devoted to eliminating oscillations of feedback force [23–25] and render high-fidelity feedback force to users. The effect of haptic rendering algorithms relies on the high-performance of haptic device. Therefore, in this paper, we focus on the performance of haptic device and human upper limb motor ability to complete teleoperation tasks and evaluate the accuracy of haptic feedback in robotic teleoperation.

Experiments are designed and carried out to measure human upper limb motor ability, the accuracy of output force from haptic devices and the fluctuation of constant output force from haptic devices. We designed two haptic devices as the master devices of robotic teleoperation [26], and an additional interface, iHandle, between haptic device and human hand was developed to measure and evaluate the interaction between haptic device and a human user. Experimental results illustrate that human hand tremble (about 2–8 degrees) plays a role in hindering the performance of haptic display if the spring-damping model is used to render feedback force in teleoperation. Our designed haptic devices iGrasp-T and iGrasp-R have a very small output force fluctuation of 0.1 N, but do not have a high accuracy, 0.92 N. Using the force sensor in iHandle can compensate for the error of output force from iGrasp-T to 0.1 N. The suggestion of using a force sensor to form a closed loop feedback force control system is given to reach an ideal accuracy of output force from haptic devices in teleoperation.

2. Principle of Experimental Evaluation on Haptic Feedback Accuracy in Teleoperation

2.1. Interaction between Human Hand and Haptic Device at the Master Side in Teleoperation

From Figure 1, in teleoperation, haptic interactions between a human user and a remote environment is usually implemented by using haptic device at the master side, slave robot with various sensors at the slave side, motion mapping methodology in master-slave control, haptic rendering algorithms to render haptic feedback, and processing methods for time delay. In the closed-loop control system, a user manipulates the haptic device to control the motion of the slave robot and senses the feedback force/torque output from the same haptic device to experience sensations at the slave side.

Slave robots usually have a much higher motion accuracy than the human hand, and high-performance force/torque sensors in the slave robot can gather extremely accurate interaction force signals. However, whether the master haptic device can truly output the high-precision measured interaction force to the user remains yet to be identified. Therefore, we present Figure 2 to decipher human manipulation and haptic feedback in the closed-loop control system.

In Figure 2, the manipulation of haptic device is divided into ideal input and noise. The ideal input cancelling the error caused by human hand tremor has high positioning accuracy, and the input noise is superimposed over the ideal input signal. No input noise is interpreted as a smooth and extremely accurate master–slave motion mapping. Accordingly, the feedback force exerted by haptic device to the user is also divided into the ideal output and the output noise. The ideal output plays the true interaction force measured at the slave side, and the output noise is superimposed over the ideal haptic feedback.

If no input noise and no output noise appear in Figure 2, the expected balanced and transparent interface is built between the user at the master side and the slave environment. It is clear that the noises in Figure 2 prevent users from smoothly controlling slave robots and truly feeling sensations in the remote environment. The determination of the input noise and output noise in Figure 2 is the prerequisite for evaluating the haptic feedback accuracy and identifying the effect of haptic display in robotic teleoperation. Measuring human upper limb motor performance and the output force accuracy of haptic device is the way to identify the final haptic display accuracy in Figure 2.

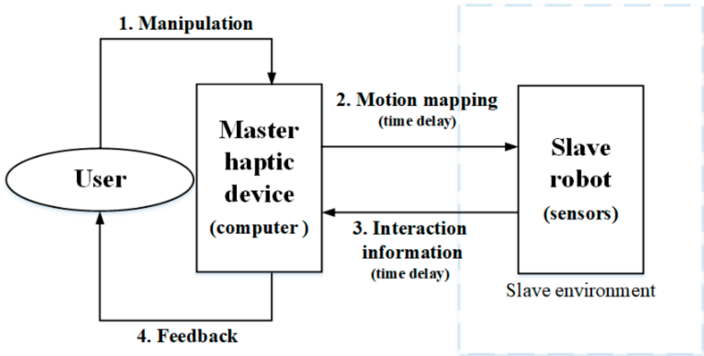


Figure 1. Description of block diagram of haptic based teleoperation.

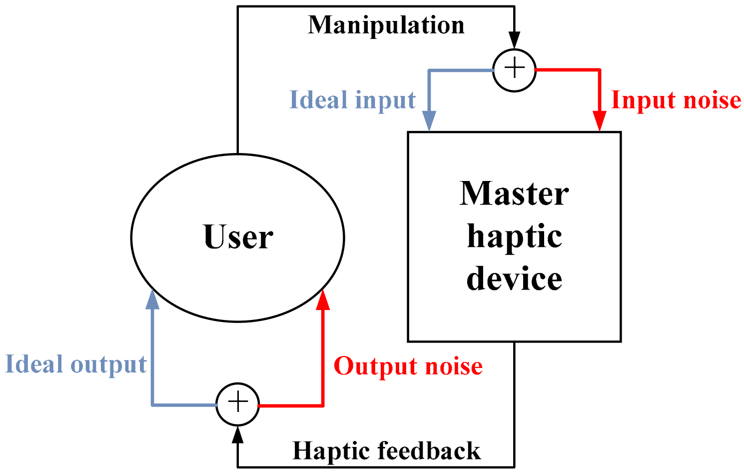


Figure 2. Relationship between human user and master haptic device in teleoperation.

2.2. iHandle: An Additional Interface between Human Hand and Haptic Device

In order to measure the input noise and the output noise in Figure 2, an interface between human hand and haptic device is a necessary requirement. The interface should measure the positioning accuracy of human upper limb and the output force accuracy of haptic device. From Figures 3 and 4, an additional interface iHandle is developed. The interface iHandle has a micro attitude and heading reference system (MAHRS 3DM-s10A) and a force/torque sensor (ATI Nano-17 SI-50-0.5), which are linked together as a whole by using a mechanical structure with a base board, a fix board, and a side wall in Figure 4a,b. The measuring accuracy of ATI Nano 17 is 0.0125 N and 0.06 N/mm, and the measuring accuracy of MAHRS is 0.1 deg, 0.1 deg and 0.5 deg. We developed measurement software using NI LabVIEW 2014 to gather experimental data. Figure 4c displays the data acquisition interface on the computer screen and Figure 4d shows the iHandle fixed at the end-effector of haptic device.

The iHandle can be individually used to measure human upper limb motor ability. A user wraps the side wall by using their palm and presses their fingers on the top cap, where the applied force/torque from the fingers can be measured by the force sensor, and the attitude of the whole structure (human hand) can be recorded by using the MAHRS fixed on the base board.

The interface iHandle can also be fixed at the end-effector of haptic device in Figure 4. A user moves or rotates the top cap to manipulate the haptic device and detects feedback force/torque through iHandle. The output force from haptic device to the user can be gathered by the ATI force sensor, and the attitude of the end-effector of the haptic device can also be measured through MAHRS.

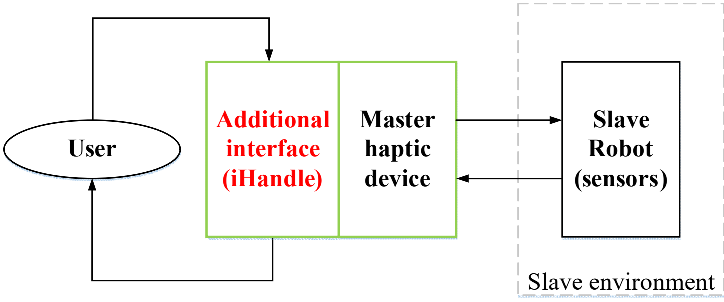
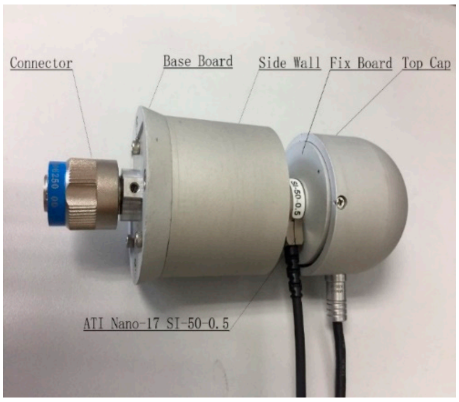
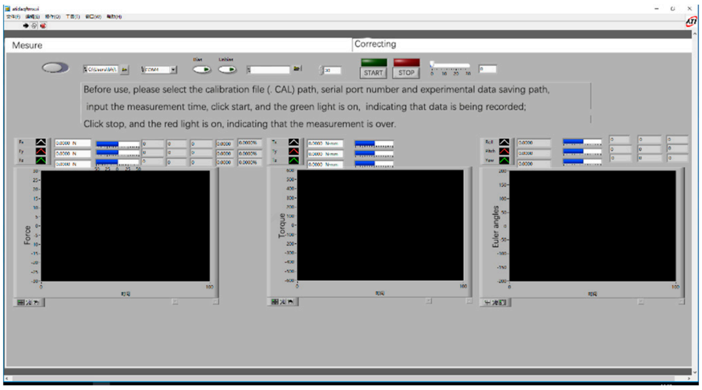


Figure 3. Description of block diagram of haptic based teleoperation.

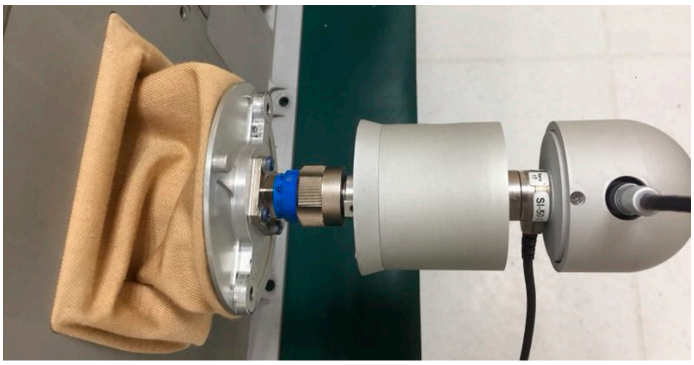


(**a**)

(**b**)



(**c**)



(**d**)

Figure 4. Composition of iHandle: (**a**,**b**) iHandle measure equipment; (**c**,**d**) human machine interface.

3. Identification of Input Noise

As shown in Figure 2, we consider the human hand tremble (hand tremor) as the input noise to haptic device, and use a posture maintenance ability and force application ability to determine the positioning accuracy of the human user.

3.1. Experiment Design by Using the iHandle

In Figure 5, a participant remains in a sitting posture, stretches their arm forward without any stabilizing support and grasps the iHandle, which imitates human hand manipulation in realistic haptic based teleoperation. The computer screen displays the information of human hand posture and the exerted force/torque on the iHandle by using graphs in real time. Positioning accuracy is determined by using human upper limb motor ability to keep hands in a required position and posture as steady as possible. At the same time, a participant can also wrap the side wall of the iHandle by using the palm and exert force on the top cap of the iHandle by using the thumb or other fingers.

The Euler angles provided by MAHRS can display the attitude of the iHandle (the posture of human hand), and the six-dimensional force and torque signals provided by the Nano 17 can describe a person's force exerted on the iHandle. Therefore, the iHandle can collect human hand tremble data and transfer the gathered information to the computer for graphic display.

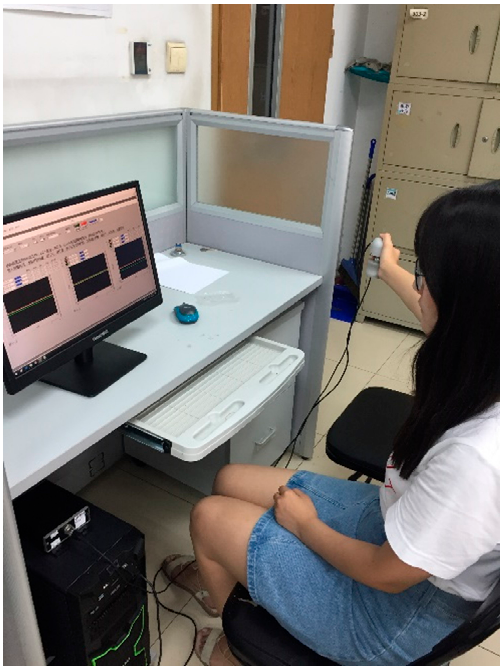


Figure 5. Scene of the experiment when a user keeps the iHandle device.

3.2. Experimental Process

During the experiment, twenty volunteers chosen were right-handed bachelor students from Beihang University, including ten men and ten women without any previous experience of neurological illness or physical injury that may influence human hand motor function. None of the participants have previous experience with the iHandle or other haptic devices.

Before the experiment, all participants were informed of the details of the experiment and given enough time to familiarize themselves with the iHandle. Each participant was required to hold the device by using one hand in a self-selected position and posture (shown in Figure 5) as steady as possible and press the top cap of the iHandle with a force close to zero N, 2 N, 10 N and 20 N for thirty seconds, respectively.

Table 1 shows the experimental regulation, and the graphic display (parameter V of Table 1) on the computer screen is an option. The check marks show the experimental scheme for each step. If the graphic display is provided, participants can view the data and graph of their exerting forces on the computer screen to regulate their exerting forces on the iHandle to reach the target values. If the graphic display is not provided, a participant can regulate the exerting force close to the required value based only on the visual cue at the beginning of the operation, no continuous visual cue is given during the whole operating process.

From Table 1, each trial has 14 steps. To eliminate the potential influence arising from the order of the experimental steps, the 14 steps of a single trial for a participant is conducted and completed in a random order. Each participant has to complete five trials, and the best performance will be chosen to determine the upper limb motor ability. Fatigue among participants was not included as a performance influencing factor since all participants had enough time to rest during the whole process of the experiment.

Table 1. All steps of the experiment to identify human upper-limb motor ability without constraining force.

Step No.	L (Left Hand)	R (Right Hand)	Force (N)	V for Exerting Force (Visual Cue from Computer Screen)	Label
1	√		0		L0
2		√	0		R0
3	√		2	√	L2V
4		√	2	√	R2V
5	√		2		L2
6		√	2		R2
7	√		10	√	L10V
8		√	10	√	R10V
9	√		10		L10
10		√	10		R10
11	√		20	√	L20V
12		√	20	√	R20V
13	√		20		L20
14		√	20		R20

3.3. Analysis of Experiment Results

Figure 6 shows the median, upper quartile, lower quartile, maximum value, minimum value and outliers of hand (iHandle) tremble of all twenty participants under each experimental condition by using a boxplot. Figure 7 shows the median, upper quartile, lower quartile, maximum value, minimum value and outliers of percentage error of exerted force on iHandle from all participants under each experimental condition by using a boxplot.

From Figure 6, it is observed that when a participant is required to keep their upper limb in a fixed position and posture for thirty seconds, the hand tremble represented by using the maximum fluctuation of iHandle attitude is mainly between 2 and 8 degrees under all experimental conditions. Table 2 shows no significant association is found between posture control and hand choice. We interpret from the experimental results that most people have a hand tremble about 2–8 degrees when they attempt to restrict their upper limb movements in a fixed position and posture. The input noise in Figure 2 should be about 2–8 degrees at least, which greatly influences the smooth motion control of slave robot (minimum positioning accuracy of 0.1 mm and 0.1 degree).

If holding a fixed posture and exerting a force are demanded at the same time, from Figures 6 and 8, the hand tremble of each participant can be reduced slightly. Notably from Figure 8, all participants exhibit best performances on maintaining steady hand posture when they are required to exert a constant force on iHandle. Half of the twenty participants achieved their best performances when the required force was about 2 N. The remaining participants achieved their best performances when the required force was larger than 2 N.

This experimental phenomenon shows that exerting a force or overcoming an oppositional force can benefit people in improving the positioning accuracy of the upper limbs even if there are individual differences in the force values among all participants (Figure 8). Experimental results show that exerting force enables participants to pay more attention to the upper limb motor and action, therefore, differentiating resistance output from haptic device should be able to help different people to improve their ability to control upper limb positioning accuracy.

From Figure 7, it is nearly impossible for people to exert an accurate force. For all participants, the maximum fluctuation percentage of exerting force value was mainly between 20% and 40%. Visual feedback greatly benefits people in improving the accuracy and lowering the fluctuation. The fluctuation percentage of an exerting force with visual display was mainly between 10% and 20%, which demonstrates that visual feedback is critical to this type of operation. Table 3 shows a significant association was found on exerting force accuracy between visual cue and no visual cue. Table 4 shows no significant association was found on exerting force between left hand and right hand. Even with a visual cue, human users were not able to exert very accurate forces on target objects. The capacity constraints of human upper limb motor control result in the input noise in robotic teleoperation (Figure 2).

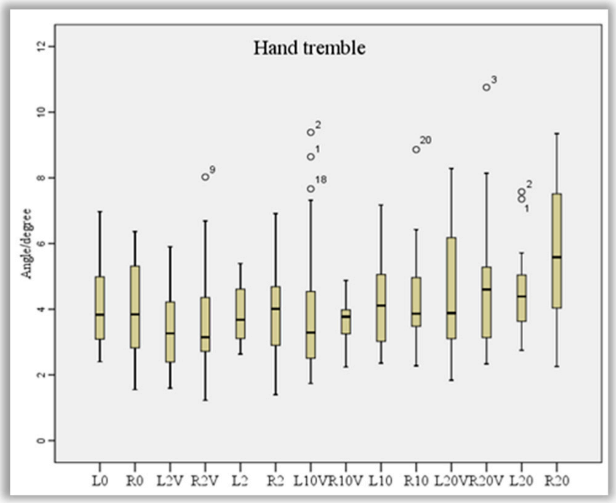


Figure 6. Hand tremble of each participant under all experimental conditions; (the label of *x*-axis is shown in Table 1-Label).

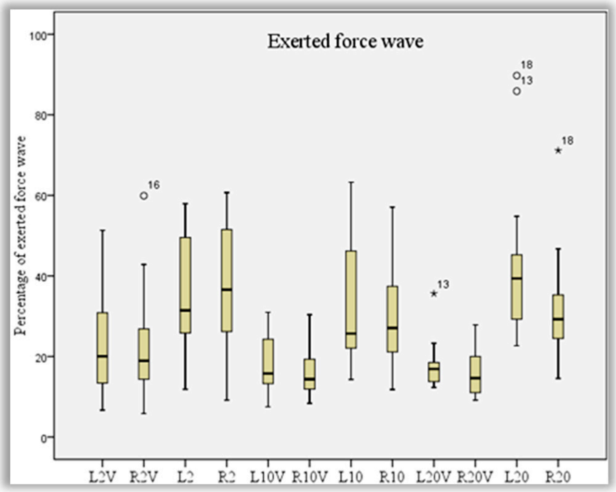


Figure 7. Percentage of exerted force wave under all experimental conditions; (the label of *x*-axis is shown in Table 1-Label).

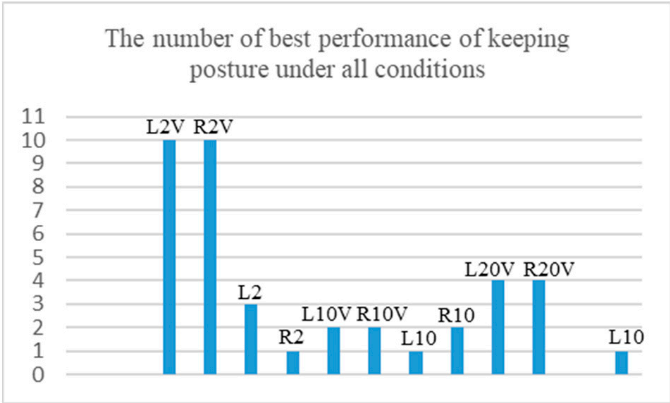


Figure 8. Number of best performance of keeping posture under all conditions.

Table 2. Tukey test results on the difference between using left and right hand on keeping posture.

No.	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
R and L	0.33782	0.33093	1.44368	0.32747	0.05	0	−0.3832	1.05885

Table 3. Tukey test result on the difference between visual cue and no visual cue on exerting force.

No.	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
V and NV	14.79673	2.40063	8.71676	0.000106	0.05	1	9.44779	20.14568

Table 4. Tukey test result on the difference between visual cue and no visual cue on exerting force.

No.	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
R and L	−1.3957	5.24047	0.37665	0.7954	0.05	0	−13.0722	10.2808

4. Identification of Output Noise: Measurement of Haptic Devices iGrasp-T and iGrasp-R Developed for Robotic Teleoperation

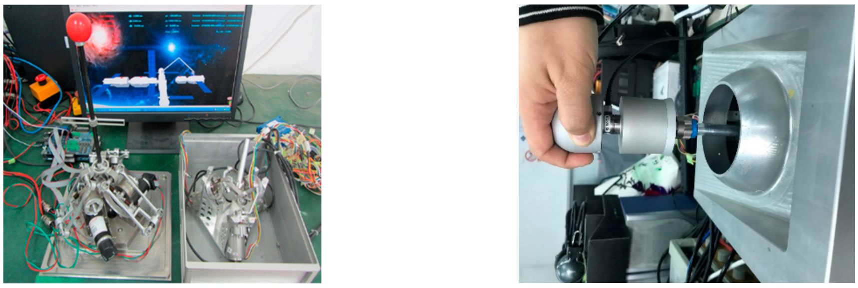
In order to identify the output force accuracy of a haptic device, we developed two haptic devices (prototypes shown in Figure 9) as the master haptic interface manipulated by a user in haptic based robotic teleoperation [26]. The two haptic devices were designed for user manipulation by using both hands at the same time. One device named iGrasp-R was designed by using a 3R parallel mechanism providing three rotational DOFs, and the other device named iGrasp-T was developed based on the DELTA mechanism to provide three translational DOFs.

The iHandle as an additional device can be fixed at the end-effector of device iGrasp-R or device iGrasp-T, respectively, in Figure 9, and the top cap of iHandle becomes the new end-effector of the combined device to be grasped and manipulated by a user.

In the experiment, we needed to measure the maximum fluctuation and accuracy of output force/torque of the two haptic devices, and identify all the factors that resulted in the output noise shown in Figure 2.

4.1. Measurement of Output Force Fluctuation without Human Hand Tremble by Using iGrasp-R and iGrasp-T

As seen in Figure 10, the end-effector of iGrasp-R or iGrasp-T can be fixed at any point in the workspace by using a black adhesive brick, and the output force/torque from haptic device without the influence of the input noise from human hand tremble can be gathered. When the end-effector of haptic device is fixed at a point in its workspace, the output force/torque value from the haptic device should constant. The measured data from ATI force sensor in iHandle should draw a straight line.



(**a**) (**b**)

Figure 9. (**a**) Two haptic devices designed for robotic teleoperation; (**b**) haptic device with iHandle.

Spring-damping model was used to render operation $\mathbf{F}_r$ resistance exerted by haptic devices to two hands of a user.

$$\mathbf{F}_r = k(\mathbf{Q}_m - \mathbf{Q}_o) + b\boldsymbol{\omega} \tag{1}$$

$$\mathbf{F}_r = k(\mathbf{P}_m - \mathbf{P}_o) + b\mathbf{v} \tag{2}$$

Equation (1) is the operation resistance model for device iGrasp-R, k is the spring coefficient, b is the damping coefficient, Q_m is the current attitude of the end-effector of device iGrasp-R, Q_o is its original attitude when it remains at the center of the whole workspace, $\boldsymbol{\omega}$ is the rotational velocity. Equation (2) is the operation resistance model for device iGrasp-T, k is the spring coefficient, b is the damping coefficient, $\mathbf{P}_m$ is the current position, $\mathbf{P}_o$ is the original position when it remains at the center of the whole workspace, $\mathbf{v}$ is the translational velocity.

We selected several points uniformly distributed in the whole workspace of each haptic device and moved or rotated the combined device to each selected point and fixed the top cap of iHandle by using the adhesive brick for thirty seconds. As the top cap of iHandle was fixed, the force sensor in iHandle could read the output force/torque from the haptic device rendered by using the spring-damping model. The end-effector of each haptic device was fixed to remain stationary without hand tremble, and the ideal measured force data should be a constant value without any fluctuation.

For the two designed haptic devices, we define the fluctuation of output force δ and the accuracy of output force ε to measure and evaluate the output performance. Accuracy is used to identify the error between the true output force and the expected output force rendered by using the haptic rendering algorithm. Fluctuation was used to evaluate the output force stability of haptic device to stably exert a feedback force.

We define the measured force $\mathbf{F}_m$ from ATI force sensor in iHandle:

$$\mathbf{F_m} = \begin{pmatrix} F_{mx} & F_{my} & F_{mz} \end{pmatrix} \tag{3}$$

We define fluctuation:

$$\delta = \max(F_{m\,max\,i} - F_{m\,min\,i})i = x, y, z \tag{4}$$

where, $F_{m\,max}$ is the maximum measured value along one coordinate axis, and $F_{m\,min}$ is the minimum measured value along one coordinate axis. We define fluctuation percentage:

$$\eta = \frac{\delta}{|\mathbf{F}_m|_{average}} \tag{5}$$

where, $|\mathbf{F}_m|_{average}$ is the average value of measured output force. We define the accuracy:

$$\varepsilon = |F_m - F_r|_{max} \tag{6}$$

The spring coefficient of the spring-damping force model is set at 0.15 N/mm for iGrasp-T and 0.12 N/deg for iGrasp-R. The spring stiffness values 0.15 N/mm for iGrasp-T and 0.12 N/deg for iGrasp-R are the maximum stable simulated stiffness of the two designed haptic devices if the maximum deformation of the virtual spring is defined to be from the device workspace center to the device workspace boundary.

For iGrasp-T, the distance from the center to the workspace boundary is about 30mm. For iGrasp-R, the angle from the center to the workspace boundary is about 30 degrees.

We gather data from six uniformly distributed points of the whole workspace for each haptic device. Observing all experimental data, for the two haptic devices iGrasp-R and iGrasp-T, the fluctuation of all output forces is smaller than 0.1 N in Figure 11. From Figure 12, the fluctuation percentage is smaller than 3%. Figure 13 shows all the twelve gathered points with the output force, fluctuation and fluctuation percentage.

To develop the two haptic devices iGrasp-R and iGrasp-T, we purchased motors from a local manufacturer and designed the control and driving system ourselves. From prior work testing reports of the motors, the motor torque fluctuation was smaller than 4%, which was achieved by rotating a motor shaft in a clockwise direction and anticlockwise direction under a specific and fixed driving current. Above experimental results illustrate that the fluctuation of the output force from a haptic device is influenced by the performance of motors and the driving system.

Although the fluctuation of the output force cannot reach the precision level of an ATI force sensor, it is much higher than the fineness of human hand perception. Therefore, we can expect the two designed haptic devices to exert acceptable high-fidelity feedback forces to users in robotic teleoperation.

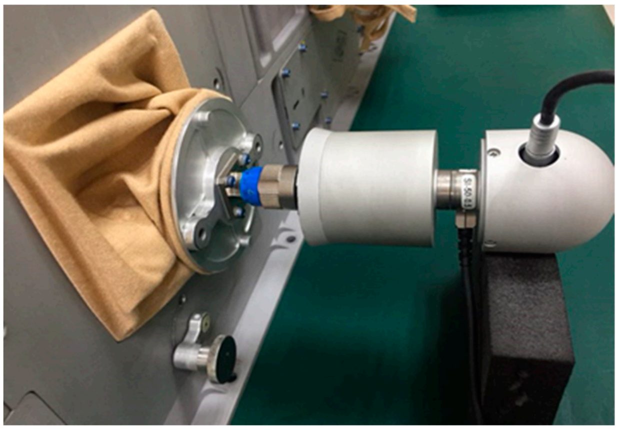


Figure 10. Bottom of the two haptic devices fixed at a point in the workspace.

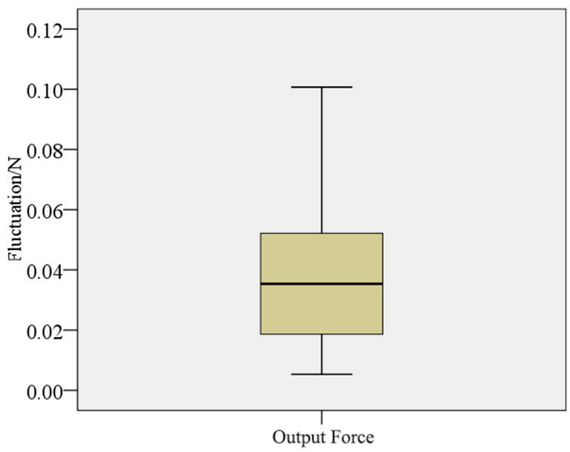


Figure 11. Fluctuation of output force under fixation.

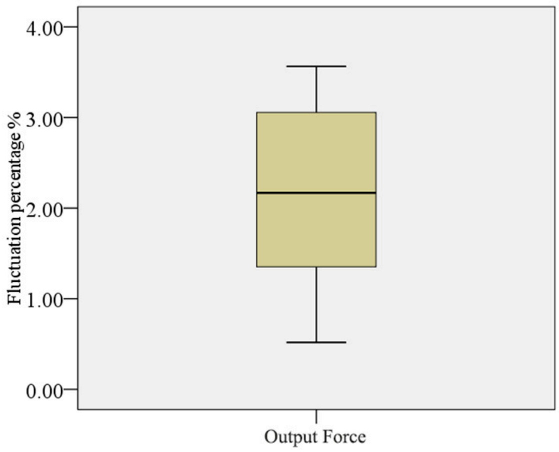


Figure 12. Fluctuation percentage of output force under fixation.

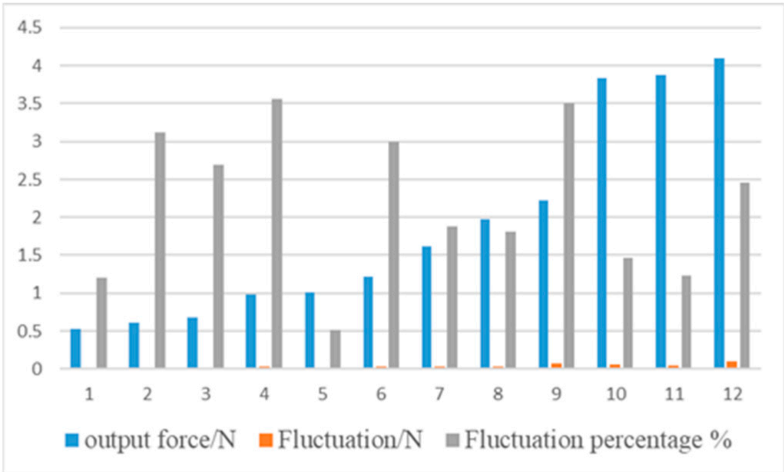


Figure 13. Output force and its fluctuation when the bottom of haptic device is fixed.

4.2. Measurement of Output Force Fluctuation under Human Manipulation by Using iGrasp-R

In order to identify the effect of human hand tremble (positioning accuracy) on output force fluctuation, all participants in the previous experiment were required to hold and maintain the end-effector (top cap) of iGrasp-R (left picture, Figure 14) stationary at several selected points in the whole workspace for thirty seconds, respectively. All the selected points are uniformly distributed in the workspace as far as possible. During the experimental process, the force sensor in iHandle gathered the output force from haptic device iGrasp-R, and the attitude of the end-effector of device iGrasp-R was read by using MAHRS. The spring coefficient of spring-damping force model k is also set to 0.12 N/deg for iGrasp-R.

However, the experimental results under human manipulation were far different from the previous experimental results with the median output force fluctuation measuring almost 0.5 N in Figure 15, and the percentage of force fluctuation measuring mainly between 20% and 40% in Figure 16. During the experiment, the hand tremble of all participants was measured to be mainly between 1 and 4 degrees, which is marginally better than the measurement results shown in Figure 6. Resistance force can certainly enable users to pay more attention to keep the end-effector of haptic device in a given position and posture. Although the input noise from human hand tremble to haptic device can be reduced by the output resistance to some extent, the output force fluctuation resulting from human hand tremble also restricts users ability to sense high-precision feedback force.

Comparing the results shown in Figures 11 and 15, the conclusion is noticeably clear that the inevitable hand tremble from human users results in acute fluctuation of output forces rendered by using the spring-damping model. Hand tremble (input noise) together with the spring-damping force model enlarges the output force fluctuation even to 1 N, which greatly hinders what users can truly feel since the slave interaction force superimposes over the operation resistance. If a user is required to keep the end-effector of haptic device at a point in its workspace to feel feedback forces gathered from the slave side, the output force fluctuation of 1 N makes it nearly impossible for a user to feel haptic feedback with high-fidelity. Therefore, haptic feedback in teleoperation is greatly influenced by human hand tremble, which is represented by the input noise to haptic device in Figure 2.

Figure 14. iGrasp-R and iGrasp-T manipulated by a user. (**a**) iHandle install at the end of iGrasp-R; (**b**) iHandle install at the end of iGrasp-T.

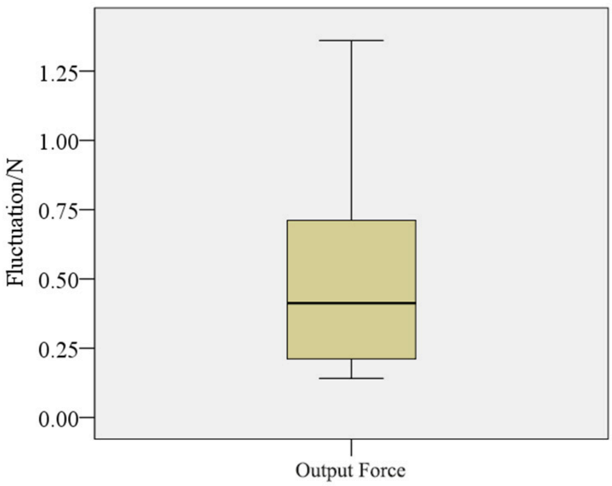


Figure 15. Fluctuation of output force under human manipulation.

4.3. Measurement of Output Force Accuracy by Using iGrasp-T

In addition to the fluctuation of output force, the accuracy of output force decides the performance and effect of haptic display in teleoperation. If the true output force from haptic device at the master side deviates significantly from the measured interaction force at the slave side, it is impossible for a user to experience and understand what is truly happening at the slave side. The effect of haptic display in teleoperation remains on collision prompting.

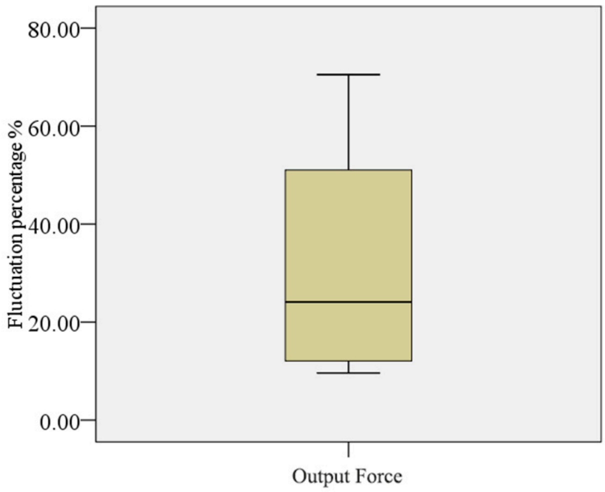


Figure 16. Fluctuation percentage of output force under human manipulation.

In order to measure the accuracy of output force from a haptic device, the relationship between the measurement coordinate system of the ATI force sensor in the iHandle and equipment coordinate system of the iGrasp-T has to be established precisely. Otherwise, coordinate errors are introduced. From the right sided picture of Figure 14, the z axis of equipment coordinate of iGrasp-T and the z axis of ATI force sensor share the same direction without error. Therefore, by developing a haptic rendering algorithm, we manipulate the haptic device iGrasp-T to exert a constant force along the z coordinate axis regardless of where its end-effector is moved to in the whole workspace. In a perfect haptic device iGrasp-T, the value measured by using the ATI force sensor in iHandle should be equal to the output force value rendered by the algorithm. The required maximum output force of iGrasp-T is 6 N, therefore, we set the constant output force 6 N along z axis.

An experienced user moves the end-effector of iGrasp-T from the center to the eight vertices of the cube workspace of iGrasp-T. The trajectories can follow a straight line, a zigzag or a curve. Irrespective of the trajectory, the perfect output force curve should be a 6 N straight line with no error. There should be no output force along x axis and y axis.

Figure 17 shows all the measured data along the z axis listed from small to large during the experiment. From Table 5, the measured largest output force along z axis is about 6.32 N, and the smallest output value is 5.08 N along the z axis. The maximum error of output force along z axis is 0.92 N and about 16%. The maximum measured output force perpendicular to z axis is 0.66 N. Although gravity compensation [26] is implemented for iGrasp-T, mechanical friction, motor output errors, manufacturing errors and assembly errors also influence the accuracy of output forces from iGrasp-T.

Table 5. Experiment result of measuring the output force accuracy of iGrasp-T.

Maximum Value along z Axis (N)	Minimum Value along z Axis (N)	Maximum Value Perpendicular to z Axis (N)	Maximum Error along z Axis (N)	Maximum Error Percentage along z Axis
6.32	5.08	0.66	0.92	16%

However, we can adjust the output force from iGrasp-T to reach the expected value 6 N by using iHandle as a feedback element. We define $\mathbf{F}_s$ as the expected output force gathered from slave side, $\mathbf{F}_a$ as the output force information sent to the controller and amplifier of iGrasp-T, $\mathbf{F}_\mathrm{h}$ as a variable added to the expected output force to enable the true output force to reach the expected value (Equation (7)).

$$\mathbf{F}_\mathrm{a} = \mathbf{F}_\mathrm{s} + \mathbf{F}_\mathrm{h} \tag{7}$$

In a perfect haptic device, $\mathbf{F}_\mathrm{s}$ equals $\mathbf{F}_\mathrm{a}$, and $\mathbf{F}_\mathrm{h}$ is zero. Due to output force errors, we can adjust the variable $\mathbf{F}_\mathrm{h}$ to enable the actual output force of the iGrasp-T to reach the interaction force measured from the slave side. According to the measured data from the force sensor in iHandle, we adjusted $\mathbf{F}_\mathrm{h}$ step by step until the actual output force reached the expected value. In fact, the variable $\mathbf{F}_\mathrm{h}$ was set to overcome the influences of all mentioned factors on output force accuracy for iGrasp-T.

We selected several points in the workspace of iGrasp-T at random to testify the proposed method (Equation (7)). By adjusting $\mathbf{F}_\mathrm{h}$ step by step, for each separate workspace point, the output force from iGrasp-T can reach 6 N with an error of about 0.2 N. Using the force sensor in iHandle can compensate for the actual output force and allow it to reach the expected value thus greatly improving the output force accuracy of haptic device iGrasp-T.

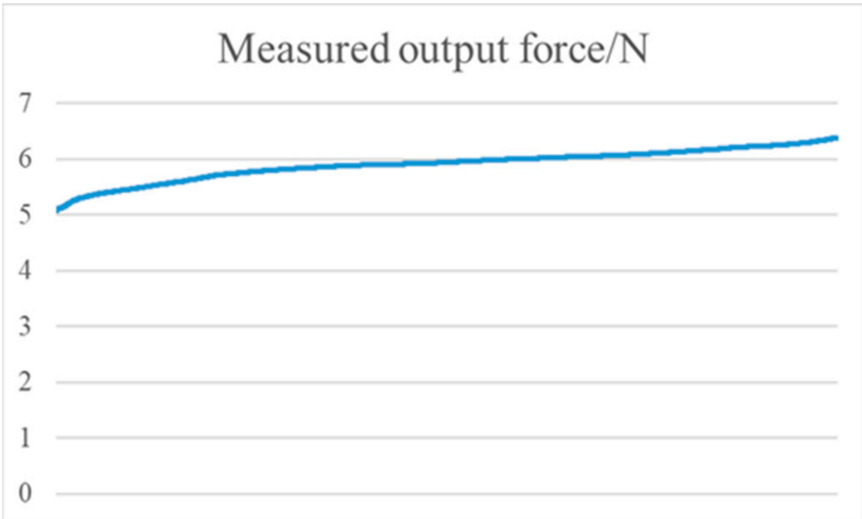


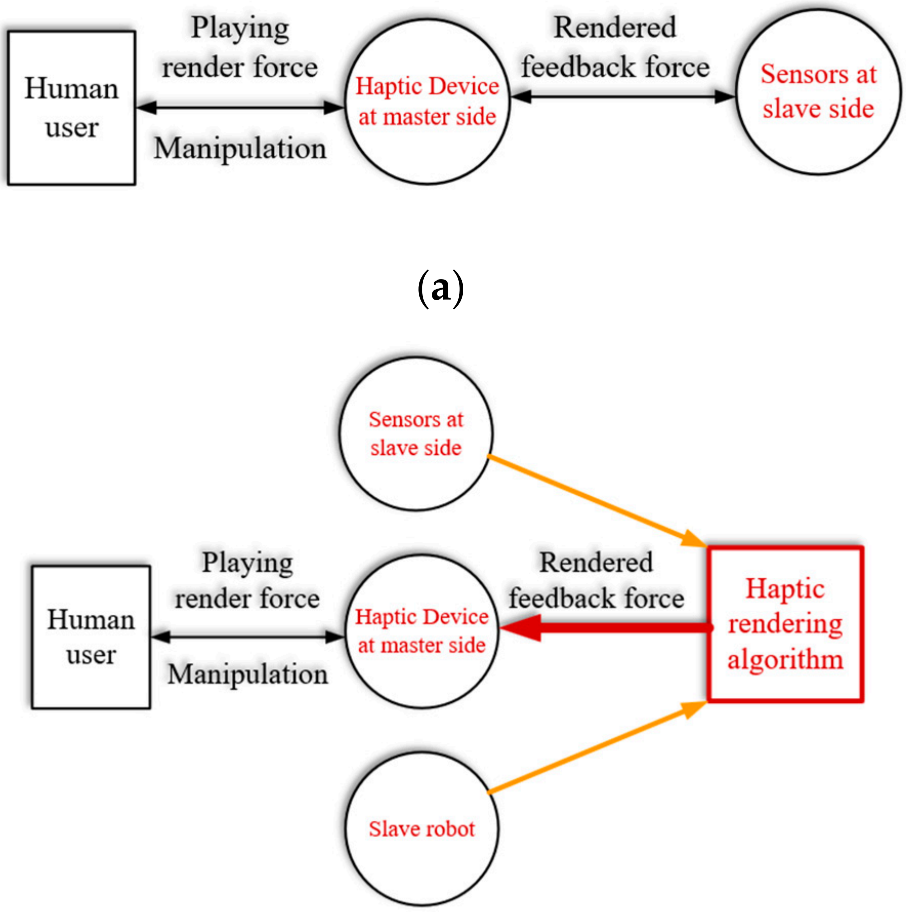
Figure 17. Measured output force while the constant force is 6 N along *z* axis.

5. Evaluation and Suggestion for Haptic Display Accuracy in Teleoperation

5.1. Haptic Rendering Discipline to Eliminate the Influence of Human Hand Tremble

Based on the experimental results, human hand tremble as input noise resulted in the fluctuation of output force from the haptic device when the spring-damping force model was used to render feedback force. The spring-damping model converts human hand tremble sensed by the haptic device into the output force fluctuation exerted by the haptic device. Therefore, the approach to eliminate the output force fluctuation was to avoid human hand motion information appearing in the haptic rendering algorithms.

Figure 18 shows the two most commonly used haptic rendering algorithms in teleoperation. The direct record and play method directly plays the measured interaction forces recorded by slave force sensors. The indirect rendering method computes the stiffness and damping coefficient based on the measured interaction forces and motion information of the slave robot, and then renders feedback forces exerted to the user by using the conventional spring-damping model.



(**b**)

Figure 18. Two types of haptic rendering algorithms for haptic based teleoperation (**a**) Direct record and play; (**b**) Indirect rendering based on measured data.

The spring-damping model was developed to render interaction forces when a user manipulates a haptic device to touch a virtual environment, and human hand motion provided the fundamental information to compute feedback force by using punishment or constraint methodology. If human hand motion information appears in the haptic rendering algorithms, human hand tremble is inevitably introduced into the rendering and output of feedback force.

However, teleoperation is different from virtual reality, high-performance force sensors (higher resolution than our designed haptic device output force) at the slave side has already recorded all interaction force information, and master haptic devices can directly output the high-resolution measured forces. No requirement of human hand motion in haptic rendering can avoid the output force fluctuation caused by input noise (Figure 2). Therefore, the direct record and play methodology which is independent of human hand motion should be adopted in haptic rendering for haptic based teleoperation.

5.2. iGrasp and iHandle Combined as One Haptic Device to Output High Accuracy Force/Torque

Figure 19 shows the analysis of output noise in haptic based teleoperation. Besides the influence of human hand tremble, the large error output force of haptic device hinders the playing of what is recorded at slave side accurately. The output noise is caused by human hand tremble and low accuracy of output force.

Regardless of whether or not the hand tremble is restricted from human hand motion information appearing in the rendering of slave interaction force, the output force error also greatly influences the feeling of a human user. Based on the experimental results, the force sensor can be used to form a closed looped output force control system. According to the measured value of force sensor of iHandle, we can adjust the value to change the output force value sent to the controller and amplifier. Finally, the actual output force can reach the expected output value. Under such conditions, the two components of output noise can both be eliminated, and the output of haptic device with high-fidelity can be achieved.

Therefore, Figure 10 shows the perfect haptic device (iHandle + iGrasp) used in robotic teleoperation. The force sensor of iHandle can be used to form a closed loop output force control system to implement an output force servo system. A conclusion can be drawn that a haptic device with a force sensor to form a closed loop force servo system should be a good solution to realize high-accuracy output force. Accurate playing slave interactions in robotic teleoperation can be implemented by using the new type of haptic device (iHandle + iGrasp).

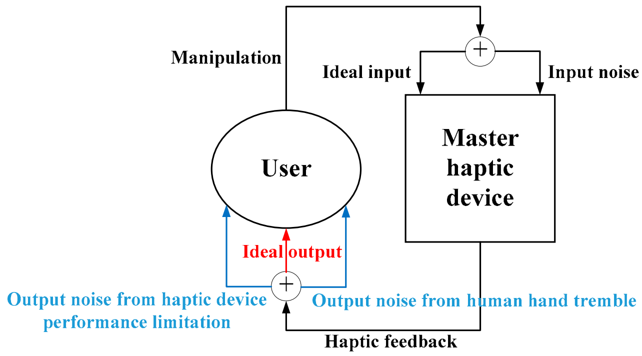


Figure 19. Analysis of the input noise and output noise of haptic based teleoperation.

6. Conclusions and Future Work

Hand tremble was measured and found to range from 2 degrees to 8 degrees revealing the inevitable input noise from a human user to a haptic device. Therefore, haptic rendering algorithms for teleoperation should avoid computing feedback forces based on human hand motions.

For our designed two haptic devices, the output fluctuation was approximately 0.1 N when no hand tremble (input noise) was introduced. The fluctuation of output force is smaller than 3%, which is close to the output torque fluctuation of selected motors. However, the error of output force in the whole workspace was notably close to 1 N. Force sensors must be used to compensate for the output force to reach the expected value.

In our future work, we will attempt using a neural network to compensate the output force of haptic devices to improve the accuracy of output force.

Author Contributions: Conceptualization, G.-Y.L.; Methodology, C.G.; Project administration, D.-T.M.; Resources, Z.W. and X.Q.; Supervision, D.-T.M., Z.W. and X.Q.; Validation, Y.W. and C.H.; Writing—original draft, Y.W. and C.H.; Writing—review & editing, G.-Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sheridan, T.B. Space teleoperation through time delay: Review and prognosis. *Autom. IEEE Trans.* **1993**, *9*, 592–606. [CrossRef]
2. Sheridan, T.B. *Telerobotics, Automation, and Human Supervisory Control*; MIT Press: Cambridge, MA, USA, 1992.
3. Hogan, N. Impedance control: An approach to manipulation. *ASME J. Dyn. Syst. Meas. Control* **1984**, *107*, 481–490.
4. Elhajj, I.; Xi, N.; Fung, W.K.; Liu, Y.H.; Li, W.J.; Kaga, T.; Fukuda, T. Haptic information in Internet-based teleoperation. *Mechatron. IEEE/ASME Trans.* **2001**, *6*, 295–304. [CrossRef]
5. Kim, W.S.; Hannaford, B.; Fejczy, A.K. Force-reflection and shared compliant control in operating telemanipulators with time delay. *IEEE Trans. Robot. Autom.* **2016**, *8*, 176–185. [CrossRef]
6. Kim, C.Y.; Kang, B.H.; Lee, M.C.; Yoon, S.M. Design of Master Console Haptic Handle for Robot Assisted Laparoscopy. *Stud. Comput. Intell.* **2013**, *466*, 333–340.
7. Meli, L.; Pacchierotti, C.; Prattichizzo, D. Experimental evaluation of magnified haptic feedback for robot-assisted needle insertion and palpation. *Int. J. Med. Robot.* **2017**, *13*, 1809. [CrossRef] [PubMed]
8. Lee, D.; Kim, U.; Choi, H.R. Development of multi-axial force sensing system for haptic feedback enabled minimally invasive robotic surgery. In Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, USA, 14–18 September 2014; pp. 4309–4314.
9. Franken, M.; Satramigioli, S.; Misra, S.; Secchi, C.; Macchelli, A. Bilateral Telemanipulation with Time Delays: A Two-Layer Approach Combining Passivity and Transparency. *IEEE Trans. Robot.* **2011**, *27*, 741–756. [CrossRef]
10. Chan, L.; Naghdy, F.; Stirling, D. Application of Adaptive Controllers in Teleoperation Systems: A Survey. *IEEE Trans. Hum.-Mach. Syst.* **2014**, *44*, 337–352.
11. Slifkin, A.B.; Newell, K.M. Noise, information transmission, and force variability. *J. Exp. Psychol. Hum. Percept. Perform.* **1999**, *25*, 837–851. [CrossRef] [PubMed]
12. Christou, E.A.; Grossman, M.; Carlton, L.G. Modeling variability of force during isometric contractions of the quadriceps femoris. *J. Mot. Behav.* **2002**, *34*, 67–81. [CrossRef] [PubMed]
13. Baweja, H.S.; Patel, B.K.; Martinkewiz, J.D.; Vu, J.; Christou, E.A. Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Exp. Brain Res.* **2009**, *197*, 35–47. [CrossRef] [PubMed]
14. Pacchierotti, C.; Tirmizi, A.; Bianchini, G.; Prattichizzo, D. Enhancing the Performance of Passive Teleoperation Systems via Cutaneous Feedback. *IEEE Trans. Haptics* **2015**, *8*, 397–409. [CrossRef] [PubMed]
15. Sakaguchi, M.; Furusho, J.; Takesue, N. Passive Force Display Using ER Brakes and its Control Experiments. In Proceedings of the IEEE Virtual Reality 2001, IEEE Computer Society, Yokohama, Japan, 13–17 March 2001; pp. 7–12.
16. Senkal, D.; Gurocak, H. Haptic joystick with hybrid actuator using air muscles and spherical MR-brake. *Mechatronics* **2011**, *21*, 951–960. [CrossRef]
17. Lee, C.D.; Lawrence, D.A.; Pao, L.Y. Isotropic force control for haptic interfaces. *Control Eng. Pract.* **2004**, *12*, 1423–1436. [CrossRef]
18. Hung, V.M.; Na, U.J. Tele-operation of a 6-DOF serial robot using a new 6-DOF haptic interface. In Proceedings of the 2010 IEEE International Symposium on Haptic Audio Visual Environments and Games, Phoenix, AZ, USA, 16–17 October 2010.
19. Ueberle, M.; Mock, N.; Buss, M. VISHARD10, a novel hyper-redundant haptic interface. In *International Conference on Haptic Interfaces for Virtual Environment and Teleoperator Systems*; IEEE Computer Society: Washington, DC, USA, 2004.
20. He, X.; Chen, Y. Six-Degree-of-Freedom Haptic Rendering in Virtual Teleoperation. *IEEE Trans. Instrum. Meas.* **2008**, *57*, 1866–1875.
21. Ryu, J.H.; Kim, J.H.; Seo, C.H.; Lim, Y.A.; Kim, J.P. A Survey of Haptic Control Technology. *Trans. Korean Soc. Mech. Eng. A* **2009**, *33*, 283–295. [CrossRef]
22. Salisbury, K.; Conti, F.; Barbagli, F. Haptic rendering: Introductory concepts. *IEEE Comput. Graph. Appl.* **2004**, *24*, 24–32. [CrossRef] [PubMed]
23. Ruffaldi, E.; Morris, D.; Edmunds, T.; Barbagli, F.; Pai, D.K. *Standardized Evaluation of Haptic Rendering Systems//Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*; IEEE Computer Society: Washington, DC, USA, 2006.
24. Wang, D.; Xiao, J.; Zhang, Y. *Evaluation of Haptic Rendering Methods//Haptic Rendering for Simulation of Fine Manipulation*; Springer: Berlin/Heidelberg, Germany, 2014.
25. Raphael, H.; Luca, M.D.; Harders, M. User-based evaluation of data-driven haptic rendering. *ACM Trans. Appl. Percept.* **2010**, *8*, 1–23.
26. Liu, G.Y.; Chen, Y.; Xie, Z.; Geng, X. GA\SQP optimization for the dimensional synthesis of a delta mechanism based haptic device design. *Robot. Comput.-Integr. Manuf.* **2018**, *51*, 73–84. [CrossRef]