Improvement of Haptic QoE on Ball-hitting Task for Bilateral Teleoperation System

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***Abstract*— To improve haptic QoE, this paper discusses what kinds of transfer functions are effective when incorporated into a control system. The evaluation is carried out by measuring subjective scores for Mobility, Sense of collision, Stability, and Total quality in a ball-hitting task. The results confirm that positive feedback is effective for a haptic interface device to compensate for viscous reaction force due to communication delay, and that negative feedback is effective for cancelling the time delay included in the robot system. It is also shown that the operator can sense, as a real feeling, the effect of the transfer function derived from the control theory.**

***Index Terms*—haptic quality of experience, bilateral teleoperation system, mean opinion score, communication delay, stability**

I. INTRODUCTION

Recently, a number of researchers have focused on remote robot systems with force feedback [1]-[3]. Force feedback enables users to touch remote objects and feel their shape, weight, and softness, and is therefore expected to significantly improve the efficiency and accuracy of work [4].

However, when haptic information such as position and/or force information is transmitted over a Quality of Service (QoS) [5] nonguaranteed network like the Internet, the QoS may seriously deteriorate [3], [4]. Moreover, in remote robot systems, when the communication delay increases, the reaction force becomes larger and instability phenomena, such as vibrations of the robot and device, may occur [6]-[8]. To solve these problems, stabilization control and QoS control must be carried out together [4].

There have long been studies on the stability of master–slave systems that use bilateral control implementing force feedback. Such studies can be divided mainly into two methods: those that use the passivity theorem and those that use the small-gain theorem.

For example, Spong et al. configured a stable bilateral control system using a scattering matrix to ensure that the communication unit fulfilled the requirements for passivity [9], while Niemeyer et al. developed a scattering matrix using a wave variable [10]. Hannaford et al. configured a bidirectional system by using a passivity observer to satisfy the passive condition [11]. Kawashima et al. reported on tele-surgery with IBIS [12]. These were conducted using velocity-force control and achieved good stability and good operability. However, if velocity information is missing due to network packet loss and/or the jitter of communication latency, velocity-force control entails the risk of causing a deviation in position between the master device held by the physician and the remote robot.

To solve this drawback, the present authors proposed a stabilization control using a wave filter together with a phase control filter for a haptic tele-control system in which 1-DoF haptic interface devices are employed in [13] and [14]. However, in position-force control, the passivity theorem could not be used, so the small-gain theorem, a control method that made the loop gain less than 1 in all frequency bands, was applied as the stability criterion. This method had the advantage of being stable in the face of arbitrary communication delay but the disadvantage of not being sufficiently operational.

On the other hand, QoS and QoE [15] in teleoperation were evaluated in [16]-[18]. In each of these papers, the effects of haptic and/or video latency due to buffering and communication delays were analyzed. Similarly, the authors assessed QoE regarding the operability of a haptic interface device for work in which a user operated an industrial robot with a force sensor at a remote location while watching video [19]. They investigated the influence of network delay on the operability and effect of the adaptive reaction force control [20]. Although the results showed that the proposed control method was effective for a teleoperation system with force feedback, it did not provide stability over a wide range of communication delays.

Now, it is strongly desirable to develop a control method that guarantees good QoE and stability over a wide range of communication. Therefore, in this paper we will improve the system in [13] while introducing the technology in [20] and try to demonstrate the enhancement of QoE. For this purpose, we introduce both a filter that assists the motion of an operator in maintaining stability and a filter that improves the frequency characteristics of the robot.

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The remainder of this paper is organized as follows. Section II describes the hardware and software of the experimental apparatus, and the experimental protocol. In Section III, the methods and results of the assessment are presented, and our interpretation is discussed. Section IV concludes the paper.

II. Construction of Bilateral Teleoperation System

A. System Configuration

The configuration of the bilateral teleoperation system with force feedback is shown in Fig. 1. The system consists of a master terminal and a slave terminal. Each terminal consists of two PCs, which are connected to each other via a switching hub.

At the master terminal, a haptic interface device (3D Systems Touch [21]) is connected to one of the PCs, and the other PC is used to display video. At the slave terminal, one of the two PCs is used for a web camera (produced by Microsoft; video resolution 1920*1080 pixels), and the other is used for an industrial robot. This robot consists of a robot arm (RV-2F-D by Mitsubishi Electric [22]), a robot controller (CR750-Q [19]), and a force sensor (1F-FS001-W200 [23]). The force sensor is attached to the end of a flange on the robot arm. The force sensor is connected to the robot controller via the force interface unit.

The master and slave terminals communicate with each other position information, which is obtained from the haptic device, as well as force information, which is obtained from the industrial robot, by the User Datagram Protocol (UDP). At the slave terminal, the command information based on the position information received from the master terminal is sent to the robot every 3.5 (ms) by a real-time control function [24]. The force information is also acquired by the real-time control function, and the information is transmitted to the master terminal by the UDP.

In our experiment, we employ a network emulator (NIST Net [25]) instead of the network shown in Fig. 1. NIST Net artificially creates various constant communication delays (called additional delays in this paper) for each packet transmitted between the master and slave terminals.

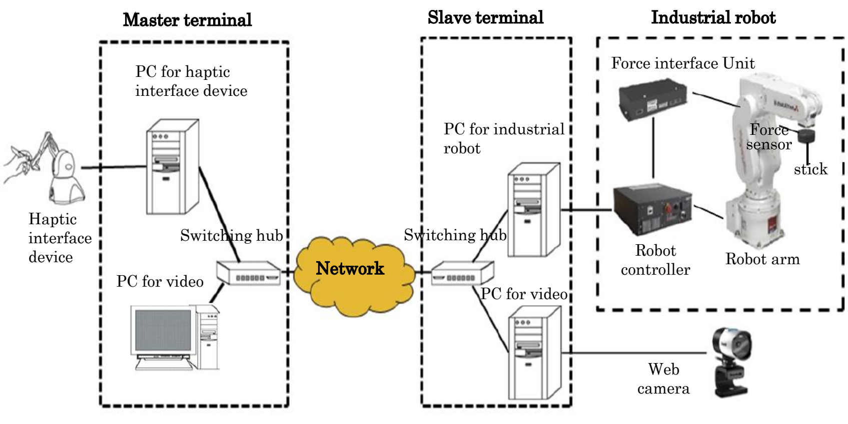


Figure 1. Configuration of bilateral teleoperation system.

B. Operator Tasks

An operator at the master terminal can operate the robot at the slave terminal by using the haptic interface device while watching video (coding scheme: Motion JPEG, average bit rate: 4.5 Mbps). The default position of the haptic interface device is set to the origin, and the position corresponds to the default position of the robot [19].

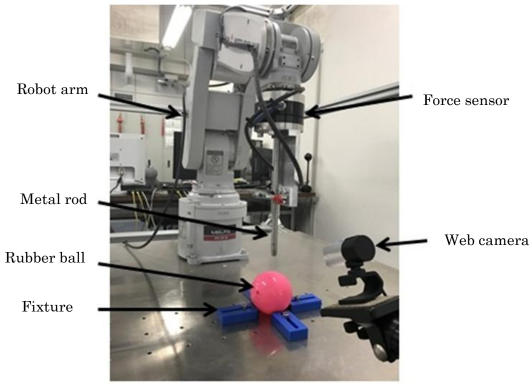


Figure 2. Experimental setup for QoE assessment.

When the operator handles the haptic interface device and moves it up or down, the position information is transmitted via the network, and the robot moves up or down according to the operator’s motion. A ball is placed under the robot and the force sensor as shown in Fig. 2. When the operator moves the robot down, the metal rod hits the ball. The hitting force is detected by the force sensor, and its information is sent to the master terminal via the slave terminal. The master terminal calculates the reaction force that the haptic interface device should generate and instructs the haptic interface device to output the reaction force. As a result, the operator can perceive the feeling of the rod hitting the ball.

In this paper, we evaluate the quality of haptic sense when the operator repeats the action of hitting the ball, and we optimize the control parameters described later.

C. Strategy to Improve Haptic QoE

In bilateral control systems, instability phenomena occur more easily as the network delay increases because it constructs a closed loop via the Internet. According to the Nyquist criterion [26] of the control theory, in a linear system, a closed loop becomes unstable when the Nyquist plot of an open loop, which can be obtained by cutting the middle of a closed loop, passes outside -1. Therefore, bilateral control becomes unstable when the phase is delayed due to a network delay and the Nyquist plot is outside -1. In other words, the system becomes unstable when the gain is greater than 1 and the phase lag is more than 180 (deg). This is an unpreventable problem when we use a network, and the underlying principle is the same as that of acoustic howling.

Several methods have been proposed to avoid instability against any communication delay. One method uses the small-gain theorem to suppress the open-loop gain to 1 or less, and another uses the passivity theorem to suppress the phase delay to less than 180 (deg). To explain these methods from the standpoint of energetics, neither the small-gain theorem nor the passivity theorem entails the amplification of energy. However, haptic QoE will deteriorate in accordance with energy consumption, although energy consumption contributes stability. Therefore, in this study we consider a control configuration that maintains haptic QoE as much as possible within the range of the reasonable communication delay that occurs in the normal Internet.

So far, the present authors have tried to stabilize a haptic tele-control system with the control block as shown in Fig. 3 [6]. Here, $G_m(s)$ is the transfer function from the generated reaction force (N) to the position of the haptic interface device (mm), $G_s(s)$ is that from the commanded position (mm) to the actual position of the industrial robot (mm), and $env(s)$ is that from the robot position (mm) to the detected reaction force (N), which depends on the stiffness of the ball. From the preliminary experiment, we identified them as (1), (2), and (3), respectively.

$$G_m(s) = \frac{50}{(0.3s+1)(0.06s+1)} \tag{1}$$

$$G_s(s) = \frac{40^2}{s^2+80s+40^2} e^{-0.04s} \tag{2}$$

$$env(s) = -5.6 \tag{3}$$

f_s is the force information detected by the force sensor and transmitted to the master terminal from the slave terminal, and f_m is the output force of the haptic interface device, which is commanded by the master terminal. x_m is the position information of the haptic interface device, which is obtained at the master terminal, and x_r is the position commanded to the industrial robot. Finally, f_h is the force exerted from the operator to the haptic interface device.

The wave filter includes the cross part, the constant coefficient 0.3, and phase control filters $Ws(s)$ and $Wm(s)$. Moreover, we incorporate a phase lead compensation filter 0.5(0.25s+1)/(0.08s+1) to $Gm(s)$ and a phase lag compensation filter 0.5(0.1s+1)/(0.5s+1)) to $Gs(s)$. The former filter is used to compensate for the phase lag caused by the second-order transfer function of $Gm(s)$. The latter filter is employed to lower the gain in high-frequency ranges in order to avoid instability. For further details, the reader is referred to [13] and [14].

This time, the transfer function $Km(s) = km\ s$ is newly fed back to $Gm(s)$, and the transfer function $Ks(s) = ks\ s$ is fed back to $Gs(s)$. Their roles and effectiveness for the haptic QoE are described in Section III. While the phase control filters $Ws(s)$ and $Wm(s)$ contribute to stabilization by suppressing high-frequency gain, they are also anticipated to have the effect of degrading haptic QoE (in particular the sense of collision) due to signal dulling. Therefore, a change in the phase control filter is also validated in Section III, and the influence of communication delay is evaluated. Note that the value of additional time is the one-way delay time, i.e., the RTT (round-trip time) is twice the additional time.

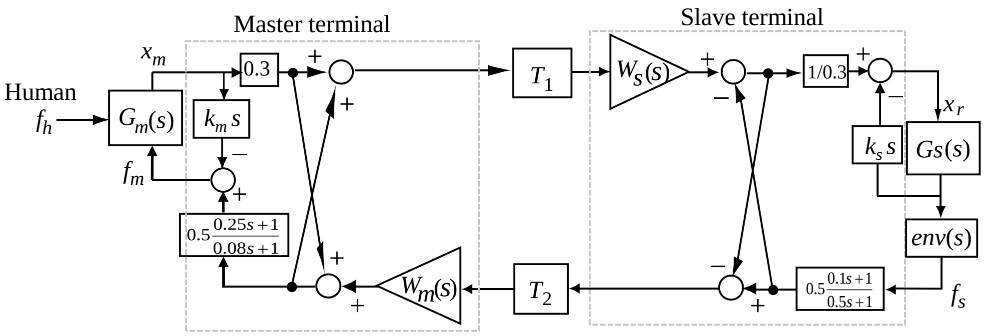


Figure 3. Control block diagram of bilateral teleoperation system.

III. Evaluation of Haptic QoE

A. Assessment Method

QoE was assessed as follows.

While watching the video from the camera, the operator remotely operated the industrial robot using the haptic interface device, and used a metal rode to push a hard tennis ball. In this operation, the operator pressed the ball 5 times (called a set) for about 10 seconds per set. The operator evaluated the degree of deterioration of each set based on the quality of the experience at the time of practice. Four factors were evaluated: Mobility, Sense of collision, Stability, and Total quality. The operator scored each factor on an evaluation sheet according to the five-grade impairment scale shown in Table I.

TABLE I. FIVE-GRADE IMPAIRMENT SCALE

Score	Description
5	Imperceptible
4	Perceptible but not annoying
3	Slightly annoying
2	Annoying
1	Very annoying

The control parameters were changed randomly for each series (a series was three consecutive sets), and the operator was not informed of the changes. As described above, the changed parameters were the gain *km* of the transfer function *Km*(*s*) of the master terminal, the gain *ks* of the transfer function *Ks*(*s*) of the slave terminal, and the transfer functions of *Wm*(*s*) and *Ws*(*s*).

The explanation of each assessed factor, collectively defined as the Haptic Quality of Experience, is as follows.

1. Mobility:

Is it easy to move the tactile interface device?

2. Sense of collision:

Is it easy to sense when the metal rod hits the hard tennis ball?

3. Stability:

Is the operation of the haptic interface device stable and not vibrating?

4. Total quality:

Comprehensive evaluation of work (the above three weighted sums) in which the weights are decided by the operator.

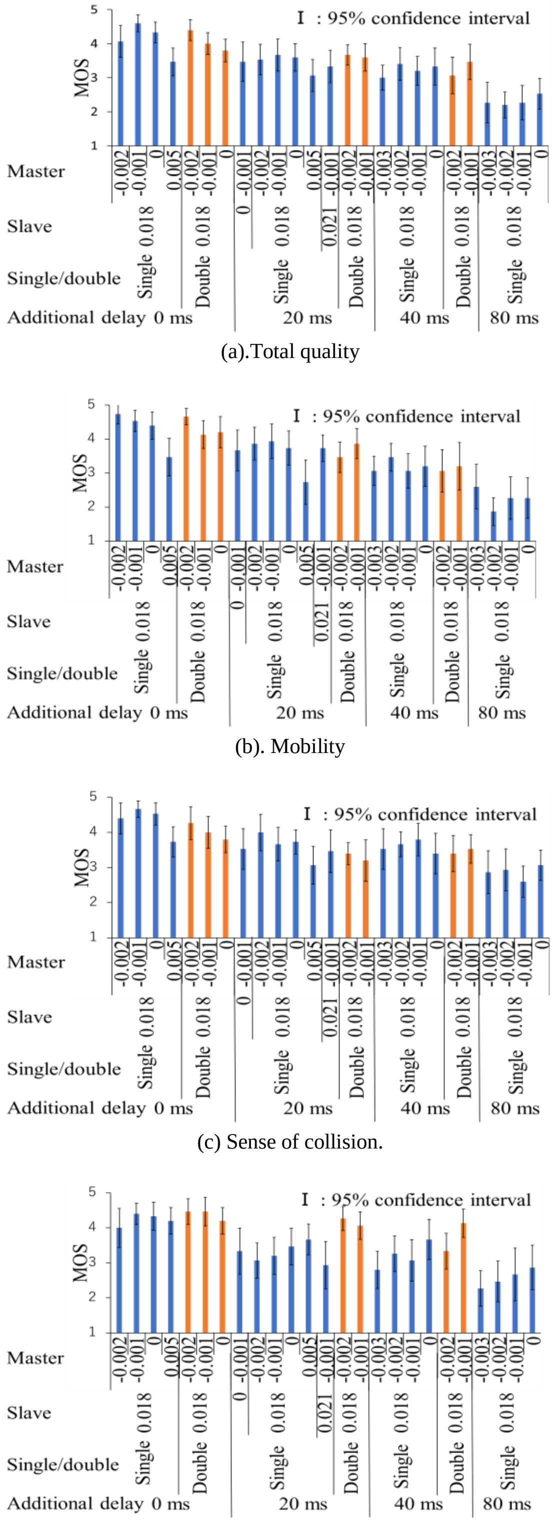
B. Experimental Results

The experiment was carried out by 17 subjects. The experimental results are shown in Fig. 4.

There were for influential factors at the horizontal axis: feedback gain *km* (Master), feedback gain *ks* (Slave), transfer functions *Ws*(*s*) and *Wm*(*s*) (Single and Double), and an artificial additional communication delay (Additional delay). Where Single means $Ws(s) = Wm(s) = 33.3/(s+33.3)$ and Double means $Ws(s) = Wm(s) = 33.3^2/(s+33.3)^2$. The value of *km* is the feedback force (N) per 1 (mm/s) velocity of the haptic interface device, and the value of *ks* is the feedback position (mm) per 1 (mm/s) velocity of the industrial robot.

The vertical value in Fig. 4 is the mean opinion score (MOS) in each condition according to the five-grade impairment scale shown in Table I, and the error bars show a 95% confidence interval.

In the preliminary experiment, the best total quality was in the case of *km* = -0.001, *ks* = 0.018, *Ws*(*s*) = *Wm*(*s*)= single, and additional delay = 0 (ms). These values were used as the evaluation standard.



(a).Total quality

(b). Mobility

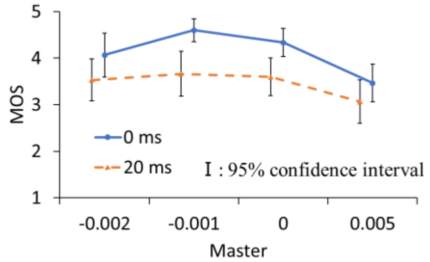
(c) Sense of collision.

(d) Stability

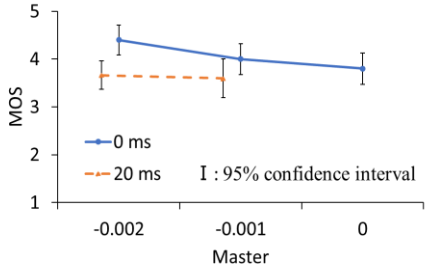
Figure 4. Experimental results of QoE evaluated by MOS.

The results for total quality in the case of *ks* = 0.018 in Fig. 4 are summarized in Fig. 5. Although the gain *km* = -0.001 was the best gain at additional delay = 0 and 20 (ms) in Single, the best gain shifted to *km* = -0.002 in the case of Double. In the same manner, the investigation of best gain *ks* summarized in Fig. 6 revealed that *ks* = 0.018, but the change was small.

The influence of communication delay was quite large. The total quality deteriorated in accordance with the increase in communication delay as shown in Fig. 7, which showed the MOS in case of *km* = -0.001, *ks* = 0.08.



(a). Single



(b). Double

Figure 5. Change in MOS according to Master gain *km*.

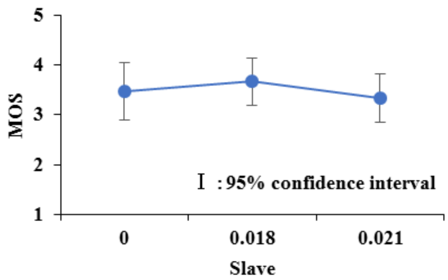


Figure 6. Change in MOS according to Slave gain *ks*.

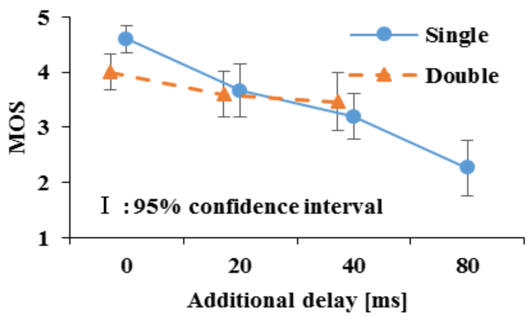


Figure 7. Change of MOS according to additional delay

C. Discussion

1) Multiple regression analysis

First, we used multiple regression analysis to investigate the effects of three evaluation factors (Mobility, Sense of collision, and Stability) on Total quality. We obtained the following equation.

$$\text{Total quality} = 0.435\ \text{Mobility} + 0.248\ \text{Sense of collision} + 0.284\ \text{Stability} \tag{4}$$

Accordingly, it became clear that Mobility had the most influence on total quality. Actually, Total quality and Mobility had very similar tendencies, as shown in Fig. 4.

2) Influence of additional delay

It is well known that the haptic QoE deteriorates with the increase in delay time. One reason for this is that the viscous resistance felt by the operator increases as the communication delay increases. This is theoretically clarified from the transfer function in the control theory [6]. Actually, even under the same experimental conditions, it is observed that the operation force that the operator feels, i.e., the reaction force, increases in the case of a large delay as shown in Fig. 8. That figure shows the transient responses of position and reaction forces on the time domain in the case of km = -0.001, ks = 0.08, and Single, where (a) is a robot motion and the force detected by the sensor and (b), (c), and (d) are the motion and reaction forces that an operator feels from the haptic interface device according to the additional delay.

The position of (b) is consistent with that of (a), and the force waveforms are also very similar. This indicates that the robot faithfully reproduces the operator's instruction motion and that the reaction force is clearly transmitted to the hand when there is no communication delay. However, a viscous reaction force of more than 1.5 (N) works in accordance with the increase in the additional delay. Moreover, the force waveform oscillates and the position waveform is not homogeneous in a 40 (ms) delay. This is the cause of the degradation of total quality.

3) Effectiveness of gain km in master terminal

To improve the haptic QoE, a factor that cancels the increasing viscous reaction force described above is necessary. This is why *km* is inevitably negative. Since the gain *km* is negatively fed back, when an operator tries to move the device, a positive *km* works as viscous reaction force that prevents movement. On the other hand, the negative *km* assists the operator’s motion. This is why negative *km* improves the QoE. However, because negative gain has the effect of amplifying energy, the system tends to become unstable due to the increase in the communication delay.

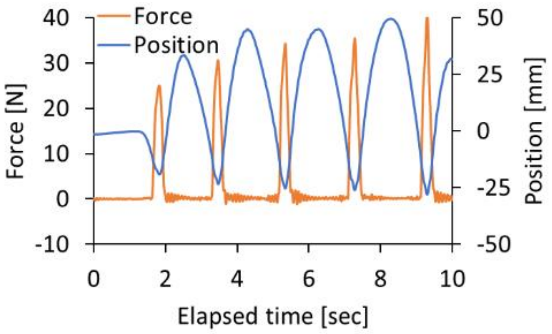
4) Effectiveness of gain ks in slave terminal

As described in (2) of Section II, the transfer function of the robot includes the time delay in itself, which destabilizes the bilateral closed loop system. To avoid this problem, we tried to incorporate ks in the slave terminal. The damping factor ks has the effect of decreasing the phase delay due to the time delay and promoting the stabilization of the closed loop. However, if ks is too large, the motion of the robot becomes slow, and the QoE may be degraded. As a compromise, ks = 0.018 is considered the best value, as shown in Fig. 6.

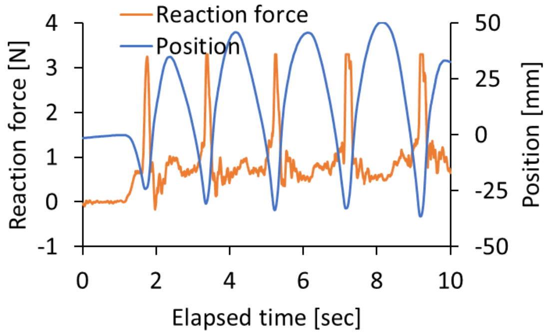
5) Relationship between haptic QoE and Ws(s)/Wm(s)

As described in Section II, the phase control filters *Ws*(*s*) and *Wm*(*s*) contribute to stabilization by suppressing high-frequency gain. On the other hand, the filters also dull the signal and consume energy because they are low-pass filters. Double has a stronger effect than Single, and the former makes the sense of collision worse. However, since the effects of energy consumption can be canceled by *km*, which generates assistance force, the difference is not clear when we compare the best value of MOS between Double and Single (Fig. 4). Actually, in a comparison between (a) and (b) in Fig. 5, a good MOS is realized by km = -0.001 in the case of Single, and it is realized by km = -0.002 in the case of Double.

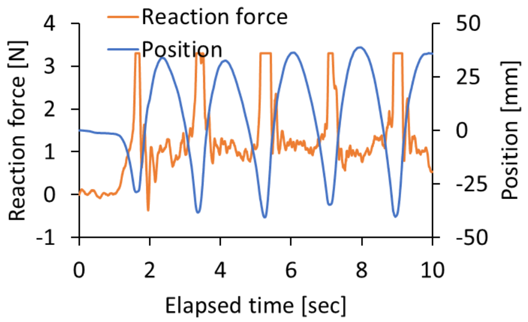
These considerations are supported by Table II, which compares the sum of MOS in the experiments under the same conditions. The total quality is almost equivalent in both cases, but the sense of collision is excellent in Single, whereas Double is particularly excellent in stability. From this, it can be seen that the transfer functions of *Ws*(*s*) and *Wm*(*s*) should be decided according to whether priority is given to stability or collision.



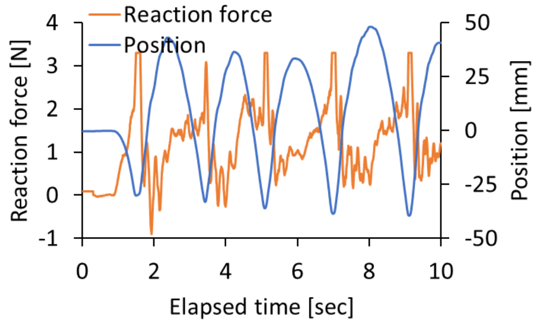
(a). Robot position and reaction force detected by sensor. Additional delay = 0 (ms)



(b). Position and registant force in haptic device. Additional delay = 0 (ms)



(c). Position and resistant force in haptic device. Additional delay = 20 (ms)



(d) Position and reaction force in haptic device. Additional delay=40 (ms).

Figure 8. Transient response of position and reaction force on time domain.

TABLE II. SUM OF MOS ACCORDING TO FILTER

	Total quality	Sense of collision	Stability	Mobility
Single	26.8	28.7	25.3	28.0
Double	26.0	25.6	28.9	26.6

IV. CONCLUSION

In this paper, to improve haptic QoE, a new transfer function was added to the conventional bilateral teleoperation system, and an assessment was performed to find the system's most appropriate parameters. The assessment was performed on 17 subjects by measuring the MOS of Mobility, Sense of collision, Stability, and Total quality. The following findings were obtained. The positive feedback that assisted the movement of the haptic interface device was effective to compensate for the viscous reaction force due to communication delay. On the other hand, the negative feedback was effective for robots to compensate for the phase delay due to the robot's own motion delay. Moreover, in the ball-hitting task, it became clear that the operator placed the highest priority on mobility, that the phase control filters *Ws*(*s*) and *Wm*(*s*) were effective for stabilization, and that the operator could also recognize the improved stability. That is, the physical effect of the transfer function derived from the control theory coincided with the human perception.

According to the authors' research, the RTT, which is twice the additional delay of this assessment, via the Internet is less than 40 (ms) inside Japan and about 80 (ms) in East Asian countries with a good network. Therefore, it was clarified that this task could be performed in Japan without causing annoyance, and between Asian countries with only slightly annoyance. Furthermore, this ball-hitting task can be perceived with a total quality score of more than 2.5 between USA and Japan, where the RTT is around 150 (ms).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S. Ishikawa, K. Kanaishi and P. Huang carried out the experiment and analyzed the experimental results. T. Miyoshi developed the theory and wrote the manuscript. Y. Ishibashi supervised the project.

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References

[1] K. Ohnishi, "Real world haptics: Its principle and future prospects," *The Journal of the Institute of Electrical Engineers of Japan*, vol. 133, o. 5, pp.268-269, May 2013. (in Japanese)
[2] T. Kawai, "Haptics for surgery," *The Journal of the Institute of Electrical Engineers of Japan*, vol. 133, no. 5, pp.282-285, May 2013. (in Japanese)
[3] Y. Ishibashi and P. Huang, "Improvement of QoS in haptic communication and its future," *IEICE Trans. Commun.*, J99-B, no. 10, pp. 911-925, Oct. 2016. (in Japanese)
[4] P. Huang and Y. Ishibashi, "QoS control and QoE assessment in multi-sensory communications with haptics," *IEICE Trans. Commun.*, E96-B, no. 2, pp.392-403, Feb. 2013.
[5] General aspects of quality of service and network performance in digital networks, ITU-T Rec. I. 350, 1993.
[6] T. Miyoshi, Y. Maeda, Y. Morita, Y. Ishibashi, and K. Terashima, "Development of haptic network game based on multi-lateral tele-control theory and influence of network delay on QoE," *Trans. the Virtual Reality Society of Japan*, Special Issues on Haptic Contents, vol. 19, no. 4, pp.559-569, Apr. 2014. (in Japanese)
[7] P. Huang, T. Miyoshi, and Y. Ishibashi, "Stability control in remote bilateral robot control system with force feedback," presented at *IEEE the 3rd International Conference on Control, Automation and Robotics (ICCAR)*, Nov. 2017.
[8] P. Huang, T. Miyoshi, and Y. Ishibashi, "Stabilization of bilateral control in remote robot system," *IEICE Technical Report*, CQ2016-125, Mar. 2017. (in Japanese)
[9] R. Anderson and M. Spong, "Bilateral Control of Teleoperators with Time Delay," *IEEE Transactions Automatic Control*, vol. 34, no. 5, pp. 494-501, May 1989.
[10] N. Tanner and G. Niemeyer, "Improving perception in time delayed Teleoperation," in *Proc. of Int. Conf. on Robotics and Automation*, 2005, pp. 356-361.
[11] B. Hannaford and J. Ryu, "Time domain passivity control of haptic interfaces," *IEEE Transactions on Robotics and Automation*, Vol.18, No.1, pp.1-10, Jan. 2002.
[12] K. Kawashima, K. Tadano, C. Wang, G. Sankaranarayanan, and B. Hannaford, "Bilateral teleoperation with time delay using modified wave variable based controller," in *Proc. of IEEE International Conference on Robotics and Automation*, 2009, pp. 4326-4331.
[13] T. Miyoshi, K. Terasima, and M. Buss, "A design method of wave filter for stabilizing non-passive operating system," in *Proc. of IEEE Int. Conf. on Control Applications (CCA)*, 2006, pp. 1318-1324.
[14] M. D. Duong, T. Miyoshi, K. Terashima, and E. J. Rodriguezseda, "Analysis and de-sign of position-force teleoperation with scattering matrix," in *Proc. 17th IFAC World Congress*, 2008, pp. 12715-12720.
[15] Definition of Quality of Experience (QoE), ITU-T Rec. G. 100/P. 10 Amendment 1, New Appendix, 2007.
[16] A. Hamam and A. El Saddik, "Evaluating the quality of experience of haptic-based applications through mathematical modeling," in *Proc. of Intl. Workshop on Haptic Audio Visual Environments and Games (HAVE)*, 2012, pp. 56-61.
[17] S. Tasaka, "Bayesian structural equation modeling of multidimensional QoE in haptic-audiovisual interactive communications," in *Proc. of Intl. Conf. on Communications (ICC)*, 2016, pp.1-6.
[18] S. Vellingiri, P. Balakrishnan, "Modeling user Quality of Experience (QoE) through position discrepancy in multi-sensorial, immersive, collaborative environments," in *Proc. of the 8th ACM on Multimedia Systems Conference*, 2017, pp.296-307.
[19] K. Suzuki, Y. Maeda, Y. Ishibashi, and N. Fukushima, "Improvement of operability in remote robot control with force feedback," in *Proc. IEEE GCCE*, 2015, pp.16-20.
[20] K. Matsunaga, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Effect of adaptive re-action force control in remote control system with haptic media and video," in *Proc. The 27th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC)*, 2012
[21] 3D Systems. [Online]. Available: https://www.3dsystems.com/haptics-devices/touch
[22] [Online]. Available:http://www.mitsubishielectric.co.jp/fa/products/rbt/robot/lineup/manual/f/bfp-a8899k.pdf (in Japanese)
[23] [Online]. Available:http://dl.mitsubishielectric.co.jp/dl/fa/members/document/manual/robot/bfp-a8940/bfp-a8940Z.pdf (in Japanese)
[24] [Online]. Available:http://dl.mitsubishielectric.co.jp/dl/fa/members/document/manual/robot/bfp-a8080/bfp-a8080e.pdf (in Japanese)
[25] M. Carson and D. Santay, "NIST Net – A Linux-based network emulation tool," *ACM SIGCOMM Computer Communication Review*, vo. 33, no. 3, pp.111-126, Mar. 2003.
[26] P. K. Ghosh and S. Anand, *Linear Control Systems*, Platinum Publishers, 2015.

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