Effect of Stabilization Control on Cooperative Work between Remote Robot Systems with Force Feedback

Qin Qian[1], Yuichi Toyoda[1], Yutaka Ishibashi[1], Pingguo Huang[2], and Yuichiro Tateiwa[1]
[1] Graduate School of Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan
[2] Faculty of Business Administration, Seijoh University, Tokai 476-8588, Japan
Email: [1] {q.qian.924, y.toyoda.694}@stn.nitech.ac.jp, {ishibasi, tateiwa}@nitech.ac.jp
[2] huangpg@seijoh-u.ac.jp

***Abstract*—In this paper, we handle the switching control, which we previously proposed as stabilization control. We investigate the effect of the switching control on cooperative work between two remote robot systems with force feedback. We also examine the influence of the network delay on hand delivery of an object as the cooperative work by experiment. In each system, a user can remotely manipulate a robot arm having a force sensor by using a haptic interface device while watching video. In our experiment, the user hand-delivers (or receives) an object between the two robot arms under the switching control and no stabilization control. Experimental results illustrate that the switching control is effective in the cooperative work, and the average work time increases as the network delay becomes larger.**

***Index Terms*—remote robot system, force feedback, stabilization control, cooperative work, experiment**

I. INTRODUCTION

Remote robot systems with force feedback have been actively researched [1]-[6]. In each system, for example, a user remotely controls a robot arm by using a haptic interface device while watching a video. By using multiple remote robot systems, we can do various types of cooperative work [7], [8]. It is possible for users to perceive the shape, smoothness, weight, and softness of a remote object with force feedback. Therefore, the efficiency and accuracy of the cooperative work are expected to be improved largely. However, when force information is transmitted over the Internet, which does not guarantee the quality of service (QoS) [9], the quality of experience (QoE) [10] such as the operability of the haptic interface device may seriously be degraded due to the network delay, delay jitter, and packet loss. Also, instability phenomena in the remote robot systems with force feedback may largely affect the remote operation. To solve the problems, it is necessary to carry out stabilization control [3]-[5] and QoS control together [2].

In [6], the authors investigate the influence of the network delay on the efficiency of cooperative work between a user and a remote robot system with force feedback by experiment. Experimental results demonstrate that the average time of work increases as the network delay becomes larger. Then, in [8], they clarify the efficiency of cooperative work between two remote robot systems with force feedback and compare the efficiency with that of work between the user and the remote robot system in [6]. As a result, they illustrate that the cooperative work between the systems has larger force than that between the user and the system. However, when the network delay is large, the systems sometimes become unstable. This is because both experiments are conducted without any stabilization control. We need to carry out stabilization control in the remote robot systems with force feedback and clarify the effect of the control.

In this paper, we handle the switching control [5], which we previously proposed as stabilization control, and investigate the effect of the switching control on hand delivery of an object between the two remote robot systems with force feedback. We also examine the influence of network delay on the hand delivery by experiment.

The rest of this paper is organized as follows. Section Ⅱ describes the remote robot system with force feedback. In Sec. Ⅲ, we introduce the switching control. Then, the experiment method is explained in Sec. Ⅳ, and experiment results are presented in Sec. Ⅴ. We conclude the paper in Sec. Ⅵ.

II. REMOTE ROBOT SYSTEMS WITH FORCE FEEDBACK

A. System Configuration

Fig. 1 shows the configuration of the remote robot systems (called *systems 1 and 2* here) with force feedback. In system 1, the master terminal consists of PC for a haptic interface device and PC for video. The haptic interface device called Geomagic Touch [11] is connected to PC for the haptic interface device. The slave terminal consists of PC for an industrial robot and PC for video. PC for the industrial robot is directly connected to the industrial robot via an Ethernet cable (100 BASE-TX). A web camera (5WH-00003 by Microsoft Corp.) is connected to PC for video, and the camera is set in front of the industrial robot. The video resolution is 1920×1080 pixels. PC for the haptic interface device and PC for the industrial robot are linked to each other by switching hubs over a network.

Manuscript received February 5, 2019; revised February 2, 2020.

doi: 10.18178/ijmerr.9.3.415-420

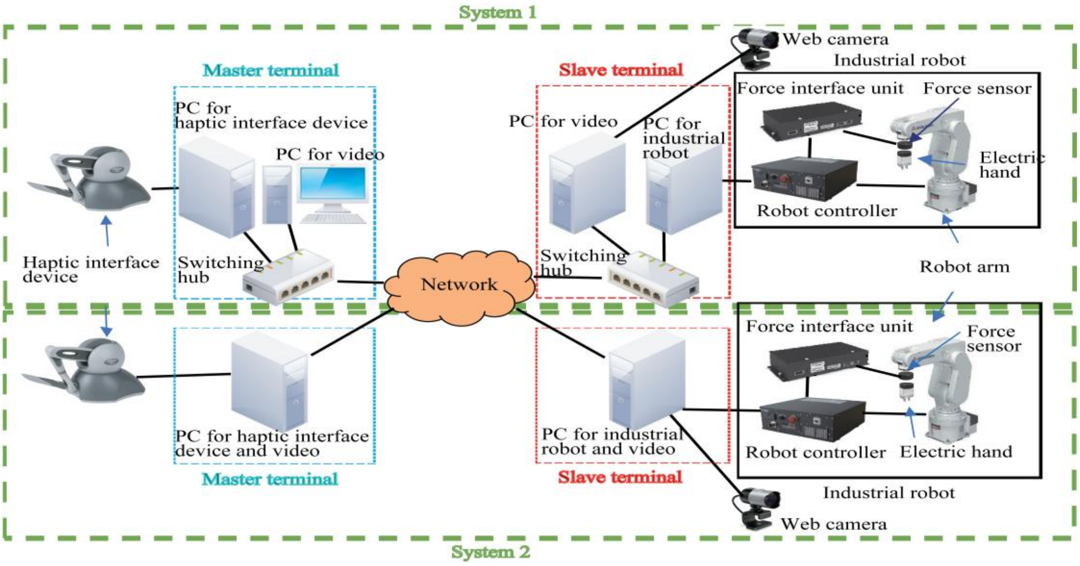


Figure 1. Configuration of remote robot systems with force feedback.

The industrial robot consists of a robot arm (RV-2F-D [12] by Mitsubishi Electric Corp.), a robot controller (CR750-Q [12]), a force interface unit (2F-TZ561 [13]), a force sensor (1F-FS001-W200 [13]) which is attached to the surface of the flange of the robot arm. In our experiment, an electric hand is attached to the tip of the force sensor. As shown in Fig. 2, the robot arm is installed on a mental platform.

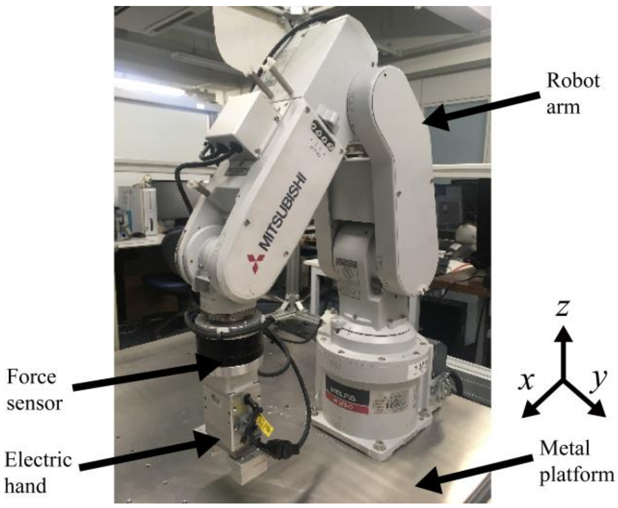


Figure 2. Appearance of robot arm.

System 2 is almost the same as system 1. In system 2, there is only one PC in each of the master and the slave terminals, and it has roles of PC not only for a haptic interface device or an industrial robot but also PC for video.

B. Remote Operation

In each system, a user can remotely operate the robot arm by using the haptic interface device. The initial position of the haptic interface device is the original position which corresponds to the initial position of the industrial robot (i.e., the electric hand attached to the tip of the robot arm). The master terminal acquires the position information from the haptic interface device every millisecond, calculates the reaction force, and outputs it via the device. Then, the position information is transmitted to the slave terminal by UDP. At the slave terminal, PC for the industrial robot employs the real-time control function [14] and real-time monitor function [14] to get the position information and the information about the force sensor from the robot controller every 3.5 milliseconds, the value of which is equal to the control period of the industrial robot. The two types of information are transmitted as different UDP packets between the robot controller and PC for the industrial robot. Then, PC for the industrial robot forwards the position information of the robot arm and force information to the master terminal. Also, it sends the information of instruction based on the position information of the haptic interface device to the industrial robot every 3.5 milliseconds.

At the master terminal, the reaction force $\boldsymbol{F}_t^{(\mathrm{m})}$ outputted at time t (ms) ($t \geq 1$) against the haptic interface device is calculated as follows:

$$\boldsymbol{F}_t^{(\mathrm{m})} = K_{\mathrm{scale}} \boldsymbol{F}_{t-1}^{(\mathrm{s})} \tag{1}$$

where $\boldsymbol{F}_t^{(\mathrm{s})}$ is the force received from the slave terminal at time t. K_{scale} is the mapping scale about the force between the industrial robot and the haptic interface device. Moreover, if the absolute value of reaction force exceeds the maximum allowable reaction force of 3.3 N, 3.3 N is outputted.

At the slave terminal, the robot arm is operated on the basis of the position information transmitted from the master terminal. The position vector about the tip of the robot arm $\boldsymbol{S}_t$ ($t \geq 1$) is calculated as follows:

$$\boldsymbol{S}_t = \boldsymbol{M}_{t-1} \tag{2}$$

where $\boldsymbol{M}_t$ is the position vector of the haptic interface device that is received from the master terminal at time *t*. In this paper, the mapping ratio from the work space of the robot arm at the slave terminal to that of the haptic interface device at the master terminal is set to 1:1 [8].

III. Stabilization Control

The switching control dynamically switches between the stabilization control by viscosity [3] and the reaction force control upon hitting [4] according to the softness. That is, the stabilization control by viscosity is carried out for soft objects, and the reaction force control upon hitting is performed for hard objects [5]. Thus, we explain the stabilization control by viscosity and the reaction force control upon hitting before our explanation of the switching control.

A. Stabilization Control by Viscosity

The stabilization control by viscosity employs the following equation of the position vector $\boldsymbol{S}_t$ instead of Eq. (2):

$$\boldsymbol{S}_t = \boldsymbol{M}_{t-1} - C_{\mathrm{d}} \left(\boldsymbol{M}_{t-1} - \boldsymbol{S}_{t-1}\right) \tag{3}$$

where C_{d} is a coefficient related to viscosity for restricting the movement distance of the industrial robot to some extent. The value of C_{d} is set to 0.95 in this paper [3].

B. Reaction Force Control upon Hitting

In the reaction force control upon hitting, the following equation of reaction force $\boldsymbol{F}_t^{(\mathrm{m})}$ is employed:

$$\boldsymbol{F}_t^{(\mathrm{m})} = \begin{cases} K_{\mathrm{scale}}\left(\boldsymbol{F}_{t-1}^{(\mathrm{m})} + K_i \boldsymbol{F}_{\mathrm{th}}\right) & \left(\left|\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})}\right| > \left|\boldsymbol{F}_{\mathrm{th}}\right|\right) \\ K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})} & (otherwise) \end{cases} \tag{4}$$

where the threshold $|\boldsymbol{F}_{\mathrm{th}}|$ is set to 0.003 N/ms. If $|\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})}| > |\boldsymbol{F}_{\mathrm{th}}|$, $\boldsymbol{F}_t^{(\mathrm{m})}$ is gradually increased by adding $K_i\boldsymbol{F}_{\mathrm{th}}$ to $\boldsymbol{F}_{t-1}^{(\mathrm{m})}$. The initial value of i is 0, and it increases by 1 every millisecond. If $|\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})}| > |\boldsymbol{F}_{\mathrm{th}}|$ again, the value of i is reset to 0 and increases by 1 every millisecond. K_i is set as follows: K_0 = 1.000, K_1 = 1.001, K_2 = 1.002, $\cdots$. Otherwise, we employ the same equation as Eq. (1).

C. Switching Control

In the switching control, we use a variable V_{flag} to judge whether an object is hard or soft. The initial value of V_{flag} is set to 0; this means that the object is soft. As in Eq. (4), if $|\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})}| > |\boldsymbol{F}_{\mathrm{th}}|$, another threshold $|\boldsymbol{F}_{\mathrm{th}}^{(\mathrm{s})}|$ (set to 0.06 N/ms [5]) is used. Then, $|\boldsymbol{F}_{t-1}^{(\mathrm{s})} - \boldsymbol{F}_{t-2}^{(\mathrm{s})}|$ is checked; if $|\boldsymbol{F}_{t-1}^{(\mathrm{s})} - \boldsymbol{F}_{t-2}^{(\mathrm{s})}| > |\boldsymbol{F}_{\mathrm{th}}^{(\mathrm{s})}|$, we set V_{flag} = 1, (this means that the object is hard). After checking, if V_{flag} = 1, the calculation methods of $\boldsymbol{F}_t^{(\mathrm{m})}$and $\boldsymbol{S}_t$ in the reaction force control upon hitting are employed. Otherwise, we set V_{flag} = 0 and use the calculation methods of $\boldsymbol{F}_t^{(\mathrm{m})}$and $\boldsymbol{S}_t$ in the stabilization control by viscosity. If $|\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\boldsymbol{F}_{t-1}^{(\mathrm{s})}| \leq |\boldsymbol{F}_{\mathrm{th}}|$, the control is switched into the stabilization control by viscosity.

IV. Experiment Method

In our experiment, we performed two types of cooperative work (called *work A* and *work B* here) in which a wooden stick of 30 cm was hand-delivered between the two robot arms under the switching control and no stabilization control in which any stabilization control is not exerted. The initial position of the two electric hands were set at the same height, and their directions were also the same.

In work A (see Fig. 3 (a)), a user (called *user 2* here) operated the robot arm (*robot arm 2*) of system 2 to move the wooden stick which was held by the electric hand toward the robot arm (*robot arm* 1) of system 1. Then, the other user (*user 1*) operated robot arm 1 to grasp the stick with closing the electric hand, and then pulled it. When user 2 perceived the force pulled by the electric hand of robot arm 1, he/she opened the electric hand to release the stick.

In work B (see Fig. 3 (b)), the wooden stick was held by robot arm 1 at the beginning of the work. User 2 moved the electric hand of robot arm 2 toward the wooden stick and closed the electric hand to grasp the stick. Then, user 1 opened the electric hand of robot arm 1 and hand-delivered the stick to user 2.

We also investigated the influence of the network delay on the hand delivery of the wooden stick by measuring the average work time. In the experiment, we produced the *additional delay* which was varied from 0 ms to 200 ms at intervals of 100 ms by using a network emulator (NIST Net [15]). We selected the additional delay for systems 1 and 2 in random order, and carried out the experiments 10 times for each of work A and work B. The average work time is defined as the average time from the moment the work is started until the instant the stick is hand-delivered. One of the authors operated robot arm 2, and another person did robot arm 1.

V. Experiment Results

The force of robot arm 2 in the *y* axis (the left and right direction) versus the elapsed time from the beginning of work B is shown in Fig. 4 under the switching control and no stabilization control when K_{scale} = 0.2. We also plot the average work time of work A versus the additional delay in system 2 when the additional delay in system 1 is 0 ms, 100 ms, and 200 ms, and that versus the additional delay in system 1 when the additional delay in system 2 is 0 ms, 100 ms, and 200 ms under the switching control when K_{scale} = 0.2 in Figs. 5 (a) and (b), respectively. Furthermore, we show those of work B in Fig. 6.

In Fig. 4 (a), we see that there is a vibration problem under no stabilization control; at about 2.5 sec., the electric hand of robot arm 2 hit the wooden stick held by the electric hand of robot arm 1, and it was stopped by error. Thus, the work became difficult to be carried out. From Fig. 4 (b), however, we find that there is no vibration problem under the switching control. Moreover, the force starts to change largely at about 4.8 sec.; this means that the stick held by robot arm 1 is hand-delivered to robot arm 2.

We also did the experiment when K_{scale} = 0.1. Then, we found that there exists no vibration problem under both switching control and no stabilization control.

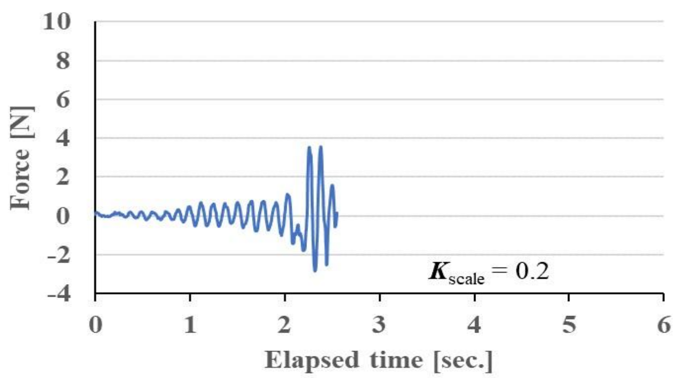
From Figs. 5 and 6, we observe that the average work times increase as the additional delays become larger in both work A and work B. Also, we note that the three lines in Figs. 5 (a) and 6 (a) are closer to each other than those in Figs. 5 (b) and 6 (b). This means that the additional delay in system 2 has larger effects on the average work time than the additional delay in system 1. This is because user 1 just opens and closes the electric hand of system 1 in work A and work B.

To compare the average work time in work A and that in work B, we replot them together in Fig. 7 when the additional delay in system 1 is the same as that in system 2. The figure reveals that the average work time in work A has almost the same tendencies as that in work B. Also, the average work time in work B is somewhat larger than that in work A; this means that it is more difficult to carry out work B than work A (that is, moving the electric hand to grasp the wooden stick is more difficult than moving to release).

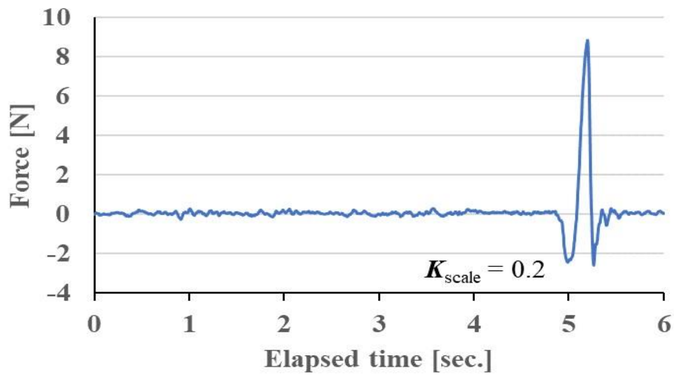
(a) Work A

(b) Work B

Figure 3. Positional relations of wooden stick between robot arms 1 and 2.

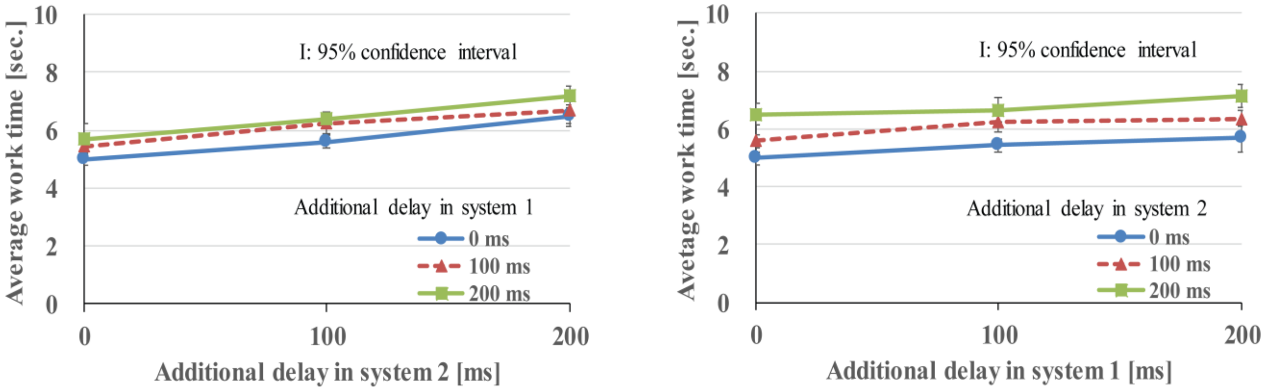


(a) No stabilization control



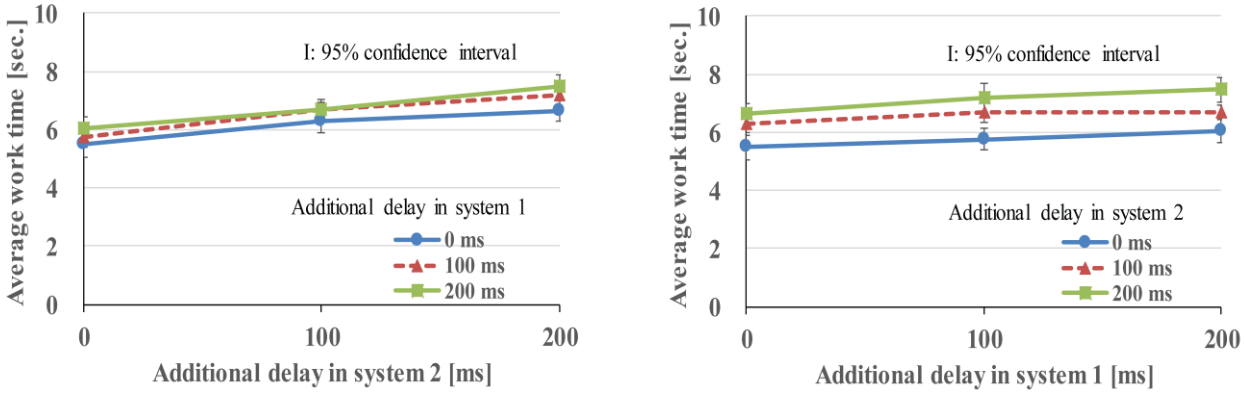
(b) Switching control

Figure 4. Force of robot arm 2 versus elapsed time.



(a) Average work time versus additional delay in system 2 (b) Average work time versus additional delay in system 1

Figure 5. Average work time of work A versus additional delay under switching control.



(a) Average work time versus additional delay in system 2 (b) Average work time versus additional delay in system 1

Figure 6. Average work time of work B versus additional delay under switching control.

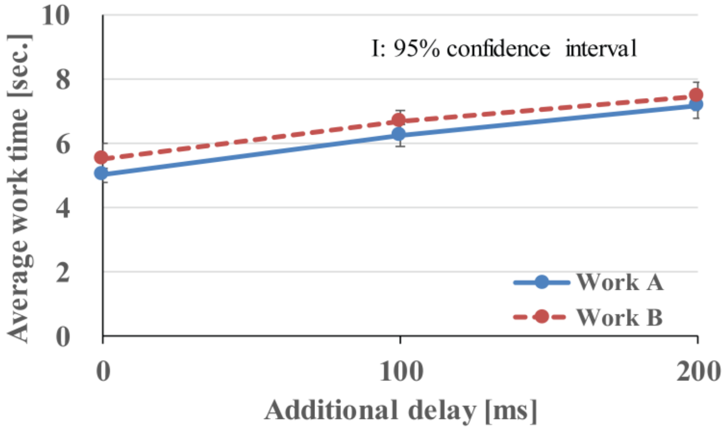


Figure 7. Average work time of switching control versus additional delay.

VI. Conclusion

In this paper, we investigated the effect of the switching control as stabilization control on hand delivery of a wooden stick between the two remote robot systems with force feedback by comparing the control and no stabilization control by experiment. We also examined the influence of the network delay on the two types work (work A and work B) of hand delivery. Experimental results demonstrated that the switching control is effective for the two types of hand delivery, and the average work time increases as the network delay becomes larger.

As the next step of our research, we need to study QoS control to reduce the average work time. We will also deal with other types of cooperative work under the switching control.

Conflict of Interest

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors conducted the research; Qin Qian and Yuichi Toyoda analyzed the data; Qin Qian wrote the paper, Yutaka Ishibashi revised the paper, and the others made some comments; all the authors had approved the final version.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 18K11261 and the Telecommunications Advancement Foundation.

REFERENCES

[1] K. Onishi, "Real world haptics: Its principle and future prospects," (in Japanese), *J. Inst. Elect. Engnr. Jpn*., vol. 133, no. 5, pp. 268–269, Mar. 2013.

[2] K. Suzuki, Y. Maeda, Y. Ishibashi, and N. Fukushima, "Improvement of operability in remote robot control with force feedback," in *Proc. The 4th IEEE Global Conference on Consumer Electronics (GCCE)*, pp. 16-20, Oct. 2015.

[3] T. Rikiishi, Y. Ishibashi, P. Huang, T. Miyoshi, H. Ohnishi, Y. Tateiwa, K. E. Psannis, and H. Watanabe, "Effect of stabilization control by viscosity in remote robot system," (in Japanese), *IEICE Technical Report*, MVE2017-19, Sep. 2017.

[4] R. Arima, P. Huang, Y. Ishibashi, and Y. Tateiwa, "Softness assessment of objects in remote robot system with haptics: Comparison between reaction force control upon hitting and stabilization control," (in Japanese), *IEICE Technical Report*, CQ2017-98, Jan. 2018.

[5] Q. Qian, Y. Toyoda, Y. Ishibashi, P. Huang, and Y. Tateiwa, "Switching between stabilization control by viscosity and reaction force control upon hitting in remote robot system with haptics," *IEICE Global Conference*, BS-2-14, Mar. 2018.

[6] Y. Toyoda, Y. Ishibashi, P. Huang, Y. Tateiwa, and H. Watanabe, "Influence of network delay on efficiency of cooperative work with human in remote robot control with haptic sense," (in Japanese), *IEICE Technical Report*, CQ2018-9, Apr. 2018.

[7] E. Taguchi, Y. Ishibashi, P. Huang, and Y. Tateiwa, "Experiment on collaborative work between remote robot systems with haptics," (in Japanese), *IEICE Global Conference*, B-11-17, Mar. 2018.

[8] Y. Toyoda, Y. Ishibashi, P. Huang, Y. Tateiwa, and H. Watanabe, "Efficiency of cooperation between remote robot systems with force feedback," in *Proc. 2018 IEEE International Conference on Electronics and Communication Engineering (ICECE)*, Dec. 2018.

[9] ITU-T Rec. I. 350, "General aspects of quality of service and network performance in digital networks," Mar. 1993.

[10] ITU-T Rec. G. 100/P. 10 Amendment 1, "New appendix I – Definition of quality of experience (QoE)," 2007.

[11] Geomagic. [Online]. Available: http://www.geomagic.com/en/products/phantomomni/overview.

[12] RV-2F-D Series Standard Specifications Manual. [Online]. Available: http://dl.mitsubishielectric.co.jp/dl/fa/members/document/manual/robot/bfp-a8900/bfp-a8900x.pdf.

[13] CR750/CR751 Controller Force Sense Function Instruction Manual. [Online]. Available: http://dl.mitsubishielectric.co.jp/dl/fa/members/document/manual/robot/bfp-a8947/bfp-a8947b.pdf.

[14] CR750/CR751 series controller, CR800 series controller Ethernet Function Instruction Manual,. [Online]. Available: http://dl.mitsubishielectric.co.jp/dl/fa/members/document/manual/robot/bfp-a3379/bfp-a3379b.pdf.

[15] M. Carson and D. Santay, "NIST Net - A Linux-based network emulation tool," *ACM SIGCOMM*, vol. 33, no. 3, pp. 111-126, July 2003.

Qin Qian received the B.E. degree from Changzhou Institute of Technology, Changzhou city, Jiangsu province, China, in 2014, and is currently working toward master's degree in the Department of Computer Science, Graduate School of Engineering, Nagoya Institute of Technology. Her research interests include networked multimedia, QoS (Quality of Service) control, and QoE (Quality of Experience) assessment in remote robot system with force feedback. She is a student member of IEEE and IEICE.

Yuichi Toyoda received the B.E. degree from Nagoya Institute of Technology, Nagoya, Japan, in 2016, and is currently working toward master's degree in the Department of Computer Science, Graduate School of Engineering, Nagoya Institute of Technology. His research interests include networked multimedia, QoS (Quality of Service) control, and QoE (Quality of Experience) assessment in multimedia communication. He is a student member of IEICE.

Yutaka Ishibashi received the B.E., M.E., and Dr.E. degrees from Nagoya Institute of Technology, Nagoya, Japan, in 1981, 1983, and 1990, respectively. In 1983, he joined the Musashino Electrical Communication Laboratory of NTT. From 1993 to 2001, he served as an Associate Professor of Department of Electrical and Computer Engineering, Faculty of Engineering, Nagoya Institute of Technology. Currently, he is a Professor of Department of Computer Science, Graduate School of Engineering, Nagoya Institute of Technology. His research interests include networked multimedia, QoS control, media synchronization, and remote robot control. He is a fellow of IEICE, a senior member of IEEE, and a member of ACM, IPSJ, and VRSJ.

Pingguo Huang received the B.E. degree from Guilin Institute of Electronic Technology, Guilin, China, in 2003, and received the M.E. and Ph. D degree from Nagoya Institute of Technology, Nagoya, Japan, in 2010 and 2013, respectively. From 2013 to 2017, he served as an Assistant Professor in Tokyo University of Science. Currently, he is a Lecturer in Seijoh University. His research interests include QoS (Quality of Service) control and QoE (Quality of Experience) assessment in networked multimedia. He is a member of IEEE and IEICE.

Yuichiro Tateiwa received the B.E. degree in Intelligence and Computer Science from Nagoya Institute of Technology in 2002, M.S. degree in Human Informatics from Nagoya University in 2004, and Ph.D. degree in Information Science from Nagoya University in 2008. Currently, he is an assistant professor of Nagoya Institute of Technology, Japan. His research interests include E-learning system for network administration and programming. He is a member of ACM, IEEE, IEICE, and JSiSE.