Efficiency of Cooperation between Remote Robot Systems with Force Feedback

Comparison with Cooperation between User and Remote Robot System

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***Abstract*— In this paper, we investigate the efficiency of cooperative work between remote robot systems with force feedback by experiment. In the system, a user can manipulate a remote industrial robot having a force sensor by using a haptic interface device while watching video. In our experiment, the user hands over (or receives) an object with an electric hand of an industrial robot arm to (or from) that of the other industrial robot arm. We also compare the efficiency with that in cooperative work between a user and the remote robot system. Experimental results illustrate that the cooperative work between the systems generates larger force than that between the system and the user.**

***Index Terms*— remote robot system, force feedback, cooperation, experiment**

I. Introduction

Remote robot systems with force feedback have been actively researched [1]-[9]. Especially, many researchers are paying attention to cooperative work in which multiple robots move an object by holding the object together or one robot hands over an object to another robot [10]. Since we can feel the shape, softness and weight of a remote object by using force feedback, we can expect that the efficiency and accuracy of remote cooperative work are largely improved. However, when force information is transferred over a quality of service (QoS) [11] non-guaranteed network like the Internet, unstability phenomena such as vibrations of the robot may occur and Quality of Experience (QoE) [12] may seriously deteriorate [2] owing to the network delay, delay jitter, and packet loss [4], [5]. To solve the problems, it is necessary to carry out stabilization control and QoS control [2], [7] together. In order to achieve efficient control, we need to clarify the efficiency of cooperative work.

A remote robot system in which a user can operate an industrial robot with a force sensor at a remote location by using a haptic interface device while watching video is handled in [9]. Then, how much the operability of the haptic interface device degrades owing to the network delay is clarified. Work in which two industrial robots move an object collaboratively by using two remote robot systems in [9] is dealt with in [10], and the influence of network delay on the collaborative work is investigated. However, only cooperative work in which two industrial robots move an object by holding the object together is dealt with. It is important to handle the cooperative work in which one industrial robot hands over an object to the other industrial robot, which receives the object.

In this paper, we handle cooperative work between the two remote robot systems with force feedback. In the work, one robot hands over an object to the other robot. We also compare the efficiency of the work with that in cooperative work between a user and the remote robot system by experiment.

The rest of this paper is organized as follows. We outline the remote robot system with force feedback in Section II. Also, we describe the assessment method in Section III. Then, we present assessment results in Section IV. Finally, Section V concludes the paper.

II. Remote Robot System with Force Feedback

A. System Configuration

The configuration of the remote robot system with force feedback is shown in Fig. 1. The system consists of a master terminal and a slave terminal. The master terminal consists of PC for a haptic interface device and PC for video. The haptic interface device (Geomagic Touch [13]) is connected to the former PC. The Degree of Freedom (DoF) of the haptic interface device is 3 (the *x*, *y*, and *z* axes). 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 by an Ethernet (100BASE-TX) cable. The DoF of the industrial robot is 6 (the *x*, *y*, and *z* axes, and rotation axes of the three axes). 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.

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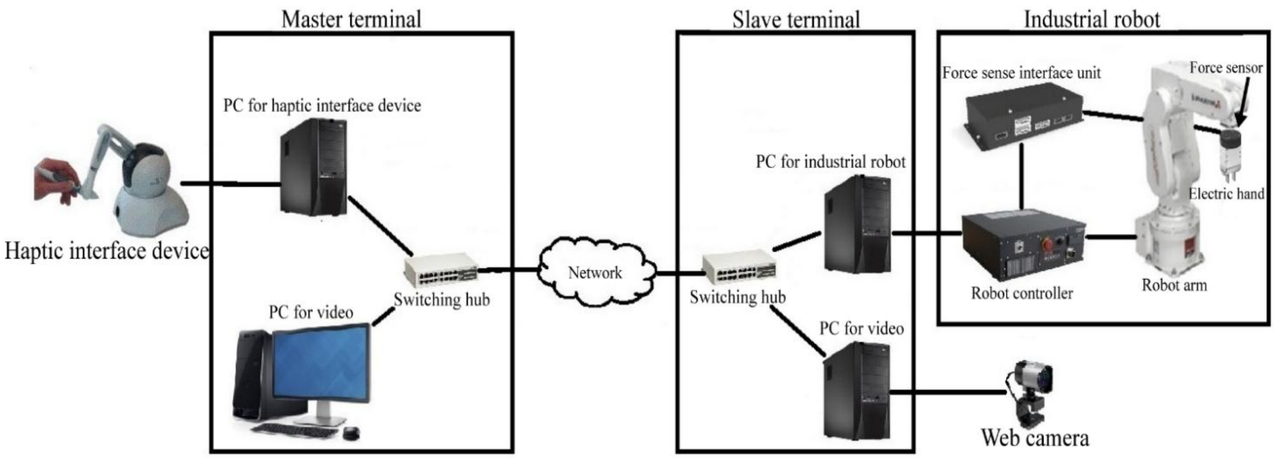

Figure 1. Configuration of remote robot system with force feedback

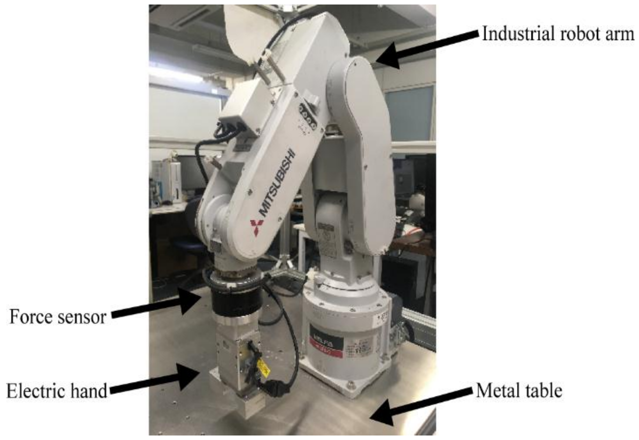

Figure 2. Appearance of industrial robot arm.

The industrial robot consists of an industrial robot arm (RV-2F-D by Mitsubishi Electric Corp. [14]), an industrial robot controller (CR750-D [14]), a force sensor (1F-FS001-W200 [15]), a force interface unit (2F-TZ561 [15]), and an electric hand (ESG1-SS-4225-11XW107 by Taiyo LTD. [16]). The force sensor is attached to a flange surface of the industrial robot arm, and the sensor is connected to the industrial robot controller via the force interface unit [9], [10]. The electric hand is fixed at the tip of the force sensor (see Fig. 2). The gripping force of the electric hand is set to 40 N, and the opening/closing velocity is set to 30 mm/s. In addition, as shown in Fig. 2, the industrial robot arm is set on a metal table.

B. Remote Control

A user at the master terminal can control the industrial robot at the slave terminal by operating the haptic interface device while watching video (the coding scheme: Motion JPEG, the average bit rate: 4.5 Mbps). The initial position of the haptic interface device is set to the origin of the device, and the position corresponds to the initial position of the industrial robot. In addition, the user can rotate the industrial robot arm along the *x*, *y* and *z* axes by inputting three keys, and the arm rotates 0.01 rad around each axis by inputting the corresponding key at one time.

The master terminal obtains the position information of the haptic interface device by the servo loop [13] (every millisecond), and calculates and outputs the reaction force (described later). Then, it sends the obtained position information to PC for the industrial robot at the slave terminal by UDP.

At the slave terminal, the real-time control function [17] of the industrial robot is used for obtaining the position information of the industrial robot and transmitting commands, and the real-time monitor function [17] is used for obtaining the information about the force sensor. At the slave terminal, the position information and the force information are obtained from the industrial robot controller every 3.5 ms, and the two types of information are transmitted to PC for the haptic interface device by UDP. PC for the industrial robot also transmits commands based on the position information received from the master terminal to the industrial robot in cycles of 3.5 ms.

The reaction force $\boldsymbol{F}_t^{(\mathrm{m})}$ applied to the haptic interface device at time t (≥ 1) is calculated as follows:

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

where $\boldsymbol{F}_t^{(s)}$ is the force received from the slave terminal at time t, and K_{scale} is a force scale which changes $\boldsymbol{F}_{t-1}^{(s)}$ so as to handle it at the haptic interface device [9], [10]. In this paper, K_{scale} is set to 0.1 by a preliminary experiment. When $|\boldsymbol{F}_t^{(m)}|$ exceeds the maximum force (3.3 N) applied to the haptic interface device, the reaction force is set to 3.3 N.

The position vector of the industrial robot $\boldsymbol{S}_t$ outputted at time t (≥ 2) is calculated as follows:

$$\boldsymbol{S}_t = \begin{cases} \boldsymbol{M}_{t-1} & (|\boldsymbol{V}_{t-1}| \leq V_{\max}) \\ \boldsymbol{M}_{t-1} + V_{\max} \dfrac{\boldsymbol{V}_{t-1}}{|\boldsymbol{V}_{t-1}|} & (otherwise) \end{cases} \qquad (2)$$

where $\boldsymbol{M}_t$ is the position vector of the haptic interface device received from the master terminal at time t, $\boldsymbol{V}_t$ is the velocity of the industrial robot at time t. $V_{\max}$ is the maximum value of velocity: in order to operate the industrial robot arm safety, the maximum value of the velocity is limited to $V_{\max}$. In this paper, $V_{\max}$ is set to 5 mm/s [9].

III. Experiment Method

In our experiment, we deal with two types of work (called *work 1* and *work 2* here) in which a wooden stick is handed over between the two industrial robots. In work 1, one industrial robot (called *robot 1*) moves a wooden stick of 30 cm toward the other industrial robot (*robot 2*) which receives the stick. In work 2, robot 1 receives the wooden stick grasped by robot 2. The initial position of the electric hand was set at the same height as the other electric hand, and the distance between the two electric hands was set to 50 mm.

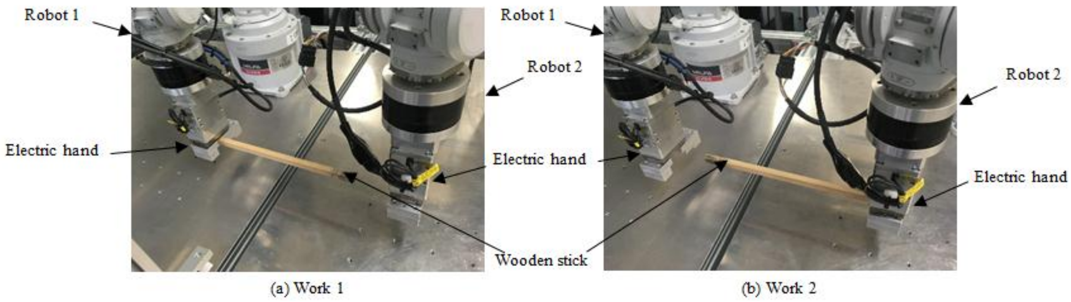

Figure 3. Positional relations of wooden stick between robots 1 and 2.

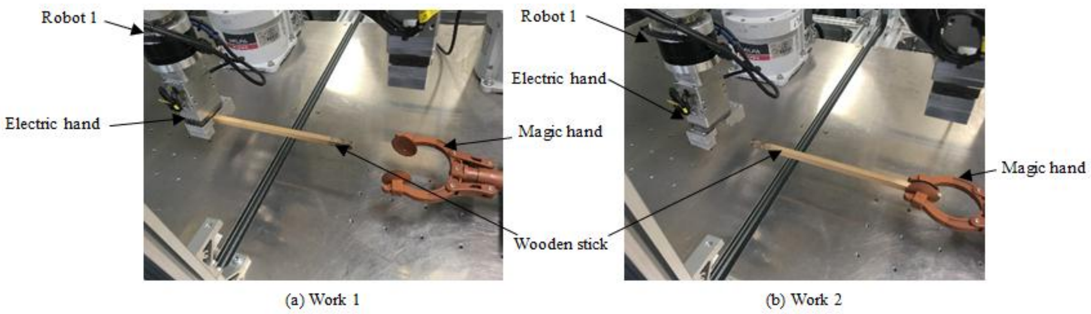

Figure 4. Positional relations of wooden stick between robot 1 and user.

In work 1, robot 1 moves the wooden stick toward robot 2 (see Fig. 3 (a)). Then, robot 2 grasps and pulls the stick with the electric hand. When the user of robot 1 who operates the haptic interface device feels the force pulled by the electric hand of robot 2, he/she opens the electric hand of robot 1 to release the stick. In work 2, at the beginning of cooperative work, the wooden stick is grasped by robot 2 (see Fig. 3 (b)). Then, robot 1 moves its electric hand toward the wooden stick grasped by robot 2. When the electric hand of robot 1 reaches a place at which the electric hand can grasp the stick, the user of robot 1 grasps the stick by using the electric hand. When the user of robot 2 confirms that the stick is grasped by the electric hand of robot 1, he/she opens the electric hand and hands over the stick to the user of robot 1.

We also carried out the experiment by using a magic hand operated by a user instead of robot 2 (see Fig. 4). For detailed of the experiment, the reader is referred to [18].

We measured the average operation time in the experiment. The average operation time is defined as the average time from the moment the work is started until the instant the stick is handed over. We carried out the experiment 10 times for each of work 1 and work 2. One of the authors operated robot 1, and a person outside the authors operated robot 2.

IV. Expreriment Results

We show the average operation times in the case of robots 1 and 2 and in the case of robot 1 and the user in Fig. 5. In the figure, we also plot the 95% confidence intervals.

From Fig. 5, we can find that there are not large differences in the average operation time between the case of robots 1 and 2 and the case of robot 1 and the user. We also see that the average operation time of work 2 tends to be larger than that of work 1.

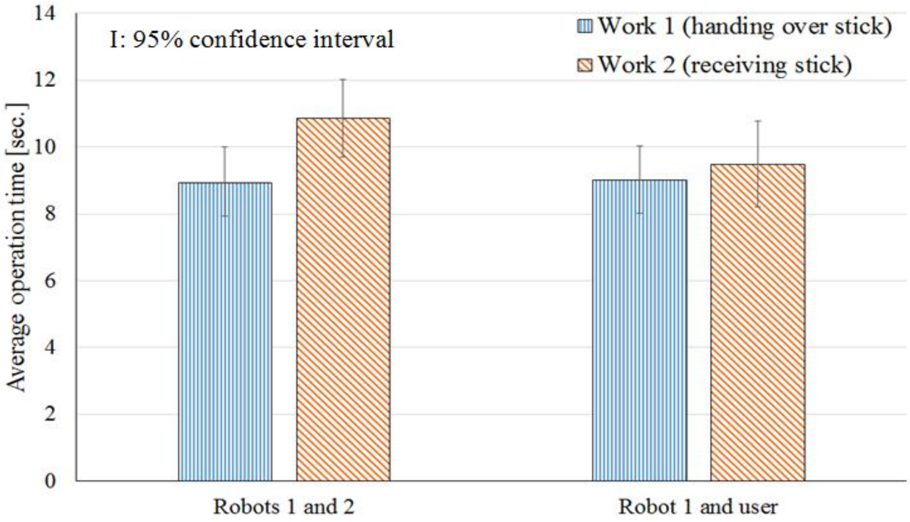

Figure 5. Average operation time.

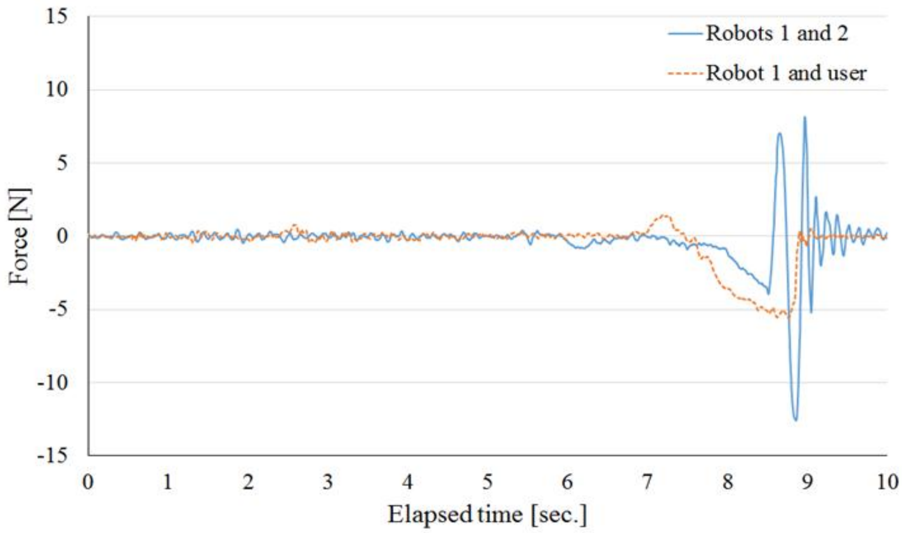

Figure 6. Force of robot 1 versus elapsed time in work 1.

In order to investigate what kinds of force are applied to the industrial robots, we measured the forces of the industrial robots from the moment the work is started until the instant the work is finished. In work 1 and work 2, since robots 1 and 2 had almost the same forces, we show only the force of robot 1 in the *y* axis (the left and right direction) versus the elapsed time from the start of the work in work 1 in Fig. 6 (The other axes had smaller force than the *y* axis).

From Fig. 6, we notice that the force in the case of robots 1 and 2 is larger than in the case of robot 1 and the user. This means that human can hand over more flexibly than the robot. We need to suppress the force so that the robot can behave as human. This is for future study.

V. Conclusion

This paper investigated the efficiency of cooperative work between the remote robot systems with force feedback by experiment. We also compared the efficiency with that in cooperative work between a user and the remote robot system. Experimental results illustrated that the average operation times of the two types of work are roughly the same, but the force between the robots is larger than that between the robot and the user.

As the next step of our research, we plan to study control that suppresses large force when the wooden stick is handed over between the remote robot systems in the experiment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors conducted the research; Yuichi Toyoda did experiment; Yuichi Toyoda and Pingguo Huang wrote the paper, Yutaka Ishibashi revised the paper, and the others made some comments; all the authors had approved the final version.

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