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Effect of Object Movement Control for Remote Robot Systems with Force Feedback

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***Abstract*—In this paper, we make a comparison among three types of object movement control in cooperative work of carrying an object between two remote robot systems with force feedback by experiment. The two robot systems have a master-slave relationship, and the slave robot automatically follows the movement of the master robot. The three types of object movement control are also compared with the case where a human performs the work instead of the robot. Furthermore, we examine the influence of the movement velocity of the object on the force applied to the object. As a result, experimental results illustrate that force in the left-right direction is more largely suppressed by the robot than by the human.**

***Index Terms*—Remote robot systems, force feedback, haptic interface device, force sensor, cooperative work**

I. INTRODUCTION

We can expect that multiple remote robot systems with force feedback have many prospective applications such as remote surgery and rescues because users can remotely control robots having force sensors by using haptic interface devices [1–10]. In such an application, it is necessary for multiple robots to move in a spatiotemporally-synchronized manner sometimes. For example, if the robots move at different heights, angles, times, and speeds when carrying an object (i.e., if the spatiotemporal synchronization between the robots is lost), large force may be applied to the object and break it.

Also, when we transmit information about force over a network that does not guarantee the Quality of Service (QoS) [11], such as the Internet, the network delay, delay jitter, and packet loss can significantly impair the Quality of Experience (QoE) [12] and make the system unstable. To solve the problems, QoS control and stabilization control should be performed together [13]. In this paper, we primarily focus on QoS control for cooperative work between two remote robot systems with force feedback to carry an object together [14–17]. The two robot systems have a master-slave relationship, and the slave robot automatically follows the movement of the master robot.

In Ref. [16], the position control using motion equation and time and distance formulas (called the *control by motion equation*) is proposed to use force information efficiently for the remote robot systems with force feedback which have a master-slave relationship. The proposed control is compared with the robot position control using force information (just called the *position control*) [15] and a method (called *human operation*) in which a human moves the object instead of one robot to clarify which one outperforms the other through experiment. As a result, experimental results demonstrated that human operation is the best.

However, we find that large force is applies to the left-right direction. This is because the object movement control has been applied to force in the front-back [16] and up-down directions [17], but the control in the left-right direction has not been carried out.

In this paper, we deal with the cooperative work in which the two robots carry an object together, and we clarify the effect of the object movement control in the left-right direction. We also handle human operation as in [16].

The rest of this paper is organized as follows. In Section II, we first outline the remote robot systems with force feedback. Next, we describe the object movement control in Section III. Then, we explain the experiment method in Section IV, and we present experimental results in Section V. Finally, Section VI concludes the paper.

II. REMOTE ROBOT SYSTEMS WITH FORCE FEEDBACK

A. Configuration of Each System

Fig. 1 shows the configuration of a remote robot system with force feedback. The system is composed of a master terminal and a slave terminal which are connected to each other via a network. The master terminal has a haptic interface device (3D Systems Touch [18]) and a display, and the slave terminal has an industrial robot and a web camera. Each terminal is composed of two PCs (PC for haptic interface device and PC for video at the master terminal, and PC for industrial robot and PC for video at the slave terminal).

The industrial robot has a robot arm (MELFA RV-2F-D by Mitsubishi Electric Corp.), a robot controller (CR750-Q), and a force interface unit (2F-TZ561). A force sensor (1F-FS001-W200) is attached to the tip of the robot arm. A toggle clamp hand is connected to the force sensor to grip an object with the toggle. In the system, a user at the master terminal can remotely operate the robot arm using the haptic interface device while monitoring the moment of the robot arm by the web camara. In this paper, we use two systems.

B. Cooperative Work between Two Systems

In this paper, we deal with cooperative work in which two systems are used to carry a wooden stick as an obejct. As shown in Fig. 2, the toggle clamp hands attached to the two robot arms grasp the wooden stick, and the stick is carried together.

The two robots should move at the same height and at the

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same movement velocity so that no large force is applied to the wooden stick. If the robots are misaligned, the wooden stick may be damaged by large force.

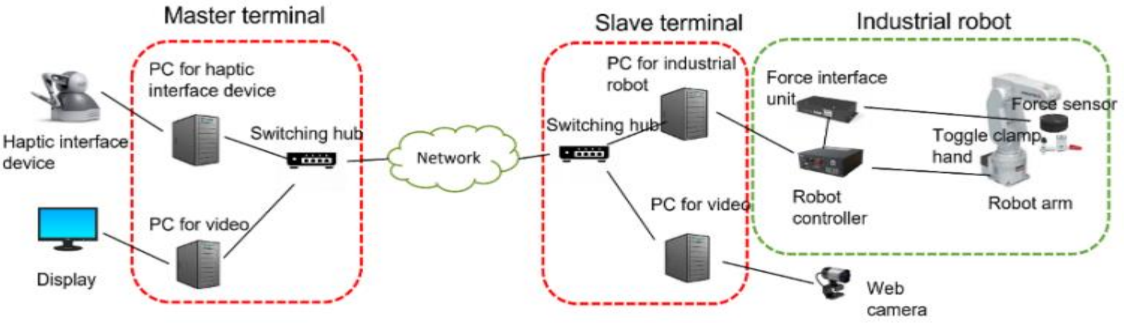


Fig. 1. Configuration of remote robot system with force feedback.

III. OBJECT MOVEMENT CONTROL

In this paper, we deal with two cases. In one case, two robots work together as shown in Fig. 2. In the other case, a human works by using a Reacher instead of one robot as shown in Fig. 3. For control in the front-back direction, in Ref. [19], we know that the control by motion equation is the closest to human operation; thus, we perform the control always (see Appendix A). In the left-right direction, three types of control are treated: No control, the position control, and the control by motion equation [16].

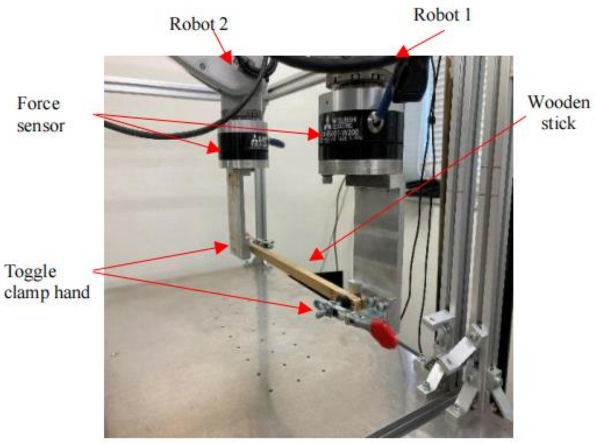


Fig. 2. Cooperative work between two robots.

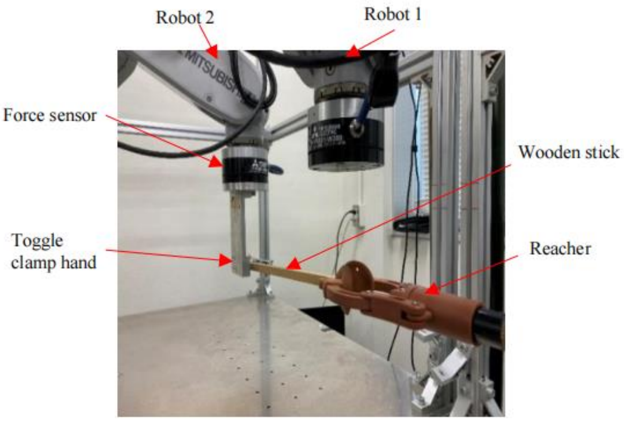


Fig. 3. Cooperative work between robot and human.

A. No Control

In this method, neither the control by motion equation nor the position control is exerted in the left-right direction.

B. Position Control

The position control finely adjusts the robot arm in a direction where the force is reduced [15]. The position control in the left-right directions automatically moves the robot arm by using the following equation [15]:

$$\boldsymbol{P}_t = a\,\boldsymbol{F}_t \tag{1}$$

where $\boldsymbol{P}_t$ is the position adjustment vector of the robot arm at time t (ms) ($t \geq 0$), $\boldsymbol{F}_t$ is the force applied to the object, and a is a coefficient which depends on the length of the wooden stick. We set $a = 0.117$ through a preliminary experiment.

C. Control by Motion Equation

The control by motion equation in the left-right direction automatically moves the robot arm by using the following equation:

$$\boldsymbol{P}_t = \begin{cases} \alpha\,\boldsymbol{P}_{t-1} + 0.112\,\boldsymbol{F}_t \ (\text{if } |\boldsymbol{P}_{t-1}| \geq 0.1 \text{ mm}) \\ 0.112\,\boldsymbol{F}_t \ (\text{otherwise}) \end{cases} \tag{2}$$

where α is 0.9 for the movement velocity of 8 mm/s, 16 mm/s, and 24 mm/s, 0.4 for that of 32 mm/s from preliminary experiment. The value of 0.112 is used in [20] when the length of the wooden stick is 30 cm. In the Appendix, the value of α is the same, but the value of 0.279 is different from 0.112. The value of 0.279 is larger than 0.112 because the wooden stick is more flexible in the front-back direction than in the left-right direction; stronger force can be applied to the left-right direction.

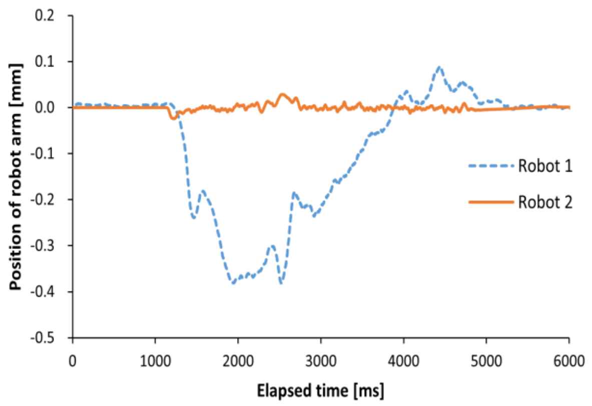
D. Human Operation

A human conducts the cooperative work instead of one robot. As shown in Fig. 3, the human grasps a wooden stick with the Reacher instead of the robot while looking at the movement of the other robot directly.

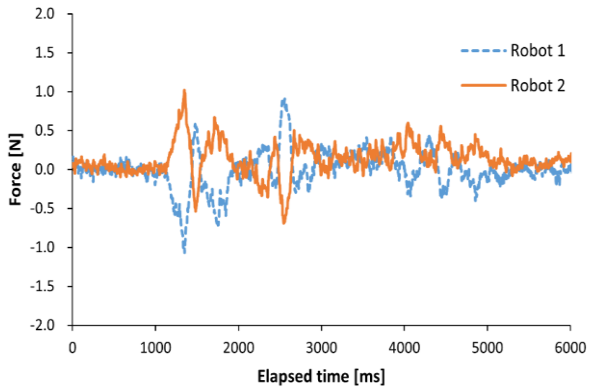
IV. EXPERIMENT METHOD

In the experiment, a wooden stick (the length: 30 cm) is moved by one robot (say *robot 1*). The other robot (*robot 2*) was moved back and forward automatically (moved 4 cm forward and 8 cm backward) for easy comparison of the four types of control including human operation. We set the movement velocity to 8 mm/s, 16 mm/s, 24 mm/s, and 32 mm/s The experiment was conducted 10 times for each movement velocity. We measured the force applied to the object during the experiment.

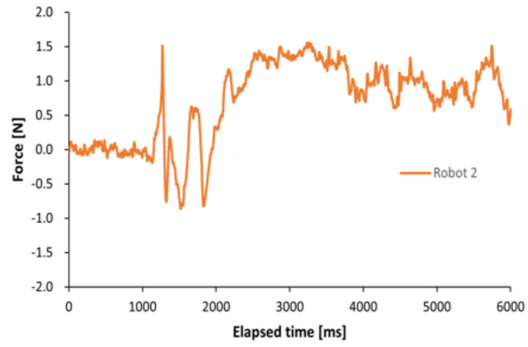
In all the types of control, the force applied to the wooden stick was measured at robot 2. Note that the force at robot 1 and that at robot 2 are opposite in direction, but they have almost the same magnitude due to the action-reaction law (see Fig. 4 (b) shown later).



(a) Position of robot arm under control by motion equation



(b) Force under control by motion equation



(c) Force in case of human operation

Fig. 6. Position and force versus elapsed time in left-right direction (velocity: 32 mm/s).

As performance measures, we obtained the average root-mean-square force and the average root-mean-square maximum force. It should be noted that smaller force applied to the wooden stick is more desirable because large force may damage the stick.

V. EXPERIMENTAL RESULTS

We show the average root-mean-square force and the average root-mean-square maximum force as a function of the movement velocity in Figs. 5 and 6, respectively. The 95% confidence intervals are also included in the figures.

From Figs. 5 and 6, we observe that the average of the control by motion equation is the smallest. We also see that the averages of the position control and control by motion equation are smaller than that of no control. The position control and control by motion equation have averages less than or almost equal to human operation. The reason is that the position adjustment in the left-right direction is very small as shown later; it is difficult for humans to make such small adjustments. On the other hand, in Ref. [16], it is shown that when the movement velocity is fast at some extent, human operation is the best in the front-back direction. This is largely different from the results in this paper. This is because the wooden stick is more flexible in the front-back direction than in the left-right direction; since the front-back has larger position differences than the left-right direction, it is easier for humans to adjust the position in the front-back direction.

To examine the relation between the control by motion equation and human operation in more detail, we show the position and force versus the elapsed time from the beginning of the experiment in Fig. 4. Since the position of human operation was almost the same as that of robot 2 under the control by motion equation, we omitted the results. In Fig. 6, we find that the control by motion equation has smaller force than human operation, especially at the beginning. This is because it is difficult for humans to detect the beginning of the robot motion and make fine adjustments. In Fig. 4 (b), we see that the force is relatively large at around 1500 ms and about 2500 ms; from Fig. 4 (a), the two robots start to move and change the direction of movement at these times, respectively. Thus, we need to reduce the force at the times. This is for further study. Furthermore, Fig. 4 (c) reveals that the force of human operation is large even after about 2500 ms. The reason is that humans are not capable of finely-adjusting the position compared to robots.

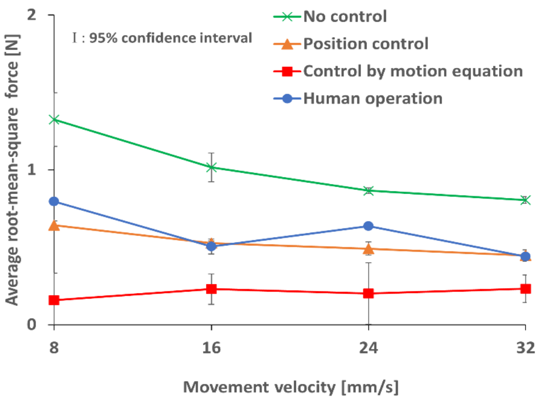


Fig. 4. Average root-mean-square force versus movement velocity.

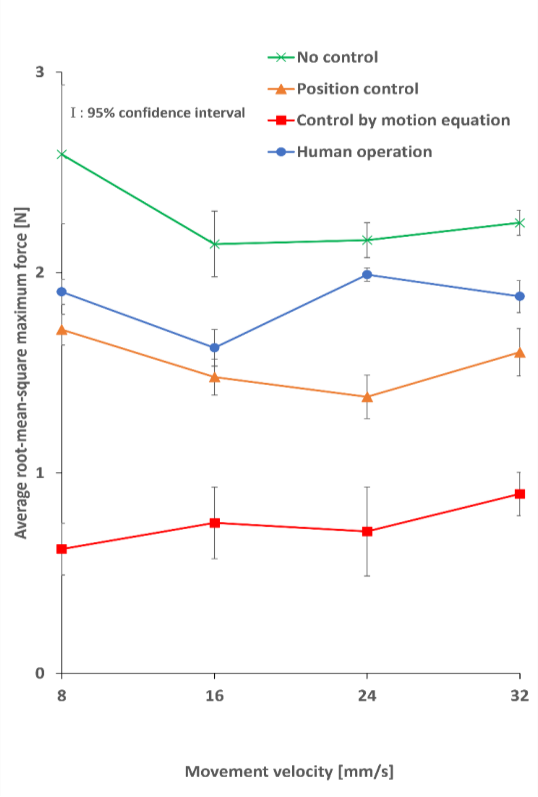


Fig. 5. Average root-mean-square maximum force versus movement velocity.

VI. CONCLUSION

In this paper, we compared four types of object movement control including human operation in cooperative work of carrying an object between two remote robot systems with force feedback by experiment. As a result, we illustrated that the control by motion equation in the left-right direction is better than the human operation.

As our future work, we plan to improve the control by motion equation in various situations. In addition, we need to reduce the force at the beginning of the movement and at the changing of the movement direction.

APPENDIX

A. Control by Motion Equation

The following equation is used to change the position of the robot arm in the front-back direction [15].

$$\boldsymbol{P}_t = \begin{cases} 0.9\,\boldsymbol{P}_{t-1} + 0.279\,\boldsymbol{F}_t \text{ (if } |\boldsymbol{P}_{t-1}| \geq 0.1 \text{ mm)} \\ \quad 0.279\,\boldsymbol{F}_t \text{ (otherwise)} \end{cases} \tag{A.1}$$

This equation is obtained based on the motion equation and time and distance formulas. To stabilize the operation, we set $\boldsymbol{P}_{t-1} = 0$ $(t \geq 1)$ when $|\boldsymbol{P}_{t-1}| < 0.1$ mm. The value of 0.279 is used in Eq. (1) of [14].

In what follows, we show how to get Eq. (A.1) when $|\boldsymbol{P}_{t-1}| \geq 0.1$ mm. Let us denote the potion vector of the robot arm by $\boldsymbol{p}_t$, the acceleration of the robot arm by $\boldsymbol{a}_t$, and the velocity of the robot arm by $\boldsymbol{v}_t$ at time t (ms). Then, the position vector $\boldsymbol{p}_{\mathrm{t+\Delta t}}$ is given by

$$\boldsymbol{p}_{\mathrm{t+\Delta t}} = \frac{1}{2}\,\boldsymbol{a}_t(\Delta t)^2 + \boldsymbol{v}_t\Delta t + \boldsymbol{p}_t \tag{A.2}$$

where Δt is the time interval $(\Delta t > 0)$ By setting $\boldsymbol{P}_{t+\Delta t} = \boldsymbol{p}_{\mathrm{t+\Delta t}} - \boldsymbol{p}_t$, we get the following equation:

$$\boldsymbol{P}_{\mathrm{t+\Delta t}} = \frac{1}{2}\,\boldsymbol{a}_t(\Delta t)^2 + \boldsymbol{v}_t\Delta t \tag{A.3}$$

Since $\boldsymbol{v}_t = (\boldsymbol{p}_{\mathrm{t}} - \boldsymbol{p}_{t-\Delta t})/\Delta t = \boldsymbol{P}_t/\Delta t$, we obtain

$$\boldsymbol{P}_{\mathrm{t+\Delta t}} = \boldsymbol{P}_t + \frac{1}{2}\,\boldsymbol{a}_t(\Delta t)^2 \tag{A.4}$$

By using the motion equation $\boldsymbol{a}_t = \boldsymbol{F}_t/m$ (m is the mass) in Eq. (A.4), we get

$$\boldsymbol{P}_{\mathrm{t+\Delta t}} = \boldsymbol{P}_t + \frac{\boldsymbol{F}_t(\boldsymbol{\Delta t})^2}{2m} \tag{A.5}$$

Since $\frac{(\Delta\, t)^2}{2m}$ is a constant, we represent the constant by K_{mov}. Also, we introduce α $(0 \leq \alpha \leq 1)$ to suppress unstable phenomena occurred when $\alpha = 1$ in a preliminary experiment as follows:

$$\boldsymbol{P}_{\mathrm{t+\Delta t}} = \alpha\boldsymbol{P}_t + K_{\mathrm{mov}}\,\boldsymbol{F}_t \tag{A. 6}$$

Through another preliminary experiment, we set $\alpha = 0.9$ and $K_{\mathrm{mov}} = 0.279$ as their optimum values when the length of the wooden stick is 30 cm. By setting $\Delta t = 1$ (that is, the unit time), we can get Eq. (A.1).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Kota Nishiyori carried out this experiment. Kota Nishiyori and Yutaka Ishibashi wrote this paper. Pingguo Huang and Yuichiro Tateiwa checked the paper. All authors had approved the final version

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