Comparison of Stabilization Control in Cooperation between Remote Robot Systems with Force Feedback

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***Abstract*— In this paper, we make a comparison among three types of stabilization control for 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. The three types of stabilization control are the reaction force control upon hitting, stabilization control by viscosity, and stabilization control with filter. In our experiment, the user employs the two systems and deals with work in which the two robots carry an object together. We perform the three types of stabilization control in each system and clarify which control is the most effective.**

***Index Terms*—remote robot system, force feedback, stabilization control, cooperation**

I. Introduction

In recent years, researches on remote robot systems with force feedback have been conducted actively [1]-[9]. In this type of system, there is a problem that the system becomes unstable due to the network delay [4]. In [4], we compare the following three types of stabilization control for work of pushing balls which have different softness by using a remote robot system with force feedback: The reaction force control upon hitting [6], the stabilization control by viscosity [7], and the stabilization control with filter [8]. As a result, it is shown that the most effective stabilization control depends on softness.

On the other hand, in [5], by using two systems each of which is employed in [4], we deal with work of moving a wooden stick cooperatively while feeling the reaction force by grasping both ends of the stick with the two robot arms. We also investigate the influence of the network delay on the work. Then, it is illustrated that as the network delay increases, the operation time becomes longer and the instability phenomenon of the system occurs more frequently. However, the stabilization control is not carried out in [5]. Because the two robot arms of the systems are connected to each other by the stick, the control in the systems is multilateral; it should be noted that the control in [4] is bilateral. Generally, it is known that the multilateral stabilization control is more difficult than the bilateral stabilization control [10]. Therefore, we need to apply the three types of stabilization control mentioned above to the work and clarify which type is the most effective for the systems in [5].

In this paper, we apply the above three types of stabilization control to the cooperative work of the systems in [5] and investigate which type of stabilization control is the most effective by experiment.

The rest of this paper is organized as follows. In Section 2, first, we explain the remote robot system with force feedback. Next, we outline the three types of stabilization control in Section 3. Then, we describe the experiment method in Section 4, and we present experiment results in Section 5. Finally, we conclude the paper in Section 6.

II. Remote Robot System with Force Feedback

A. System Configuration

Fig. 1 shows the configuration of the two remote robot systems (systems 1 and 2) with force feedback [3]-[9]. The remote robot system consists of a master terminal and a slave terminal. The master terminal is composed of PC for a haptic interface device and PC for a video which are connected to a switching hub. A haptic interface device (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 a video which are connected to a switching hub. PC for the industrial robot

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is directly connected to the industrial robot by an Ethernet (100BASE-TX) cable. Also, a Web camera is connected to PC for the video. The industrial robot has the industrial robot arm, industrial robot controller, force sensor, and haptic interface unit. A force sensor is attached to the tip of the industrial robot arm.

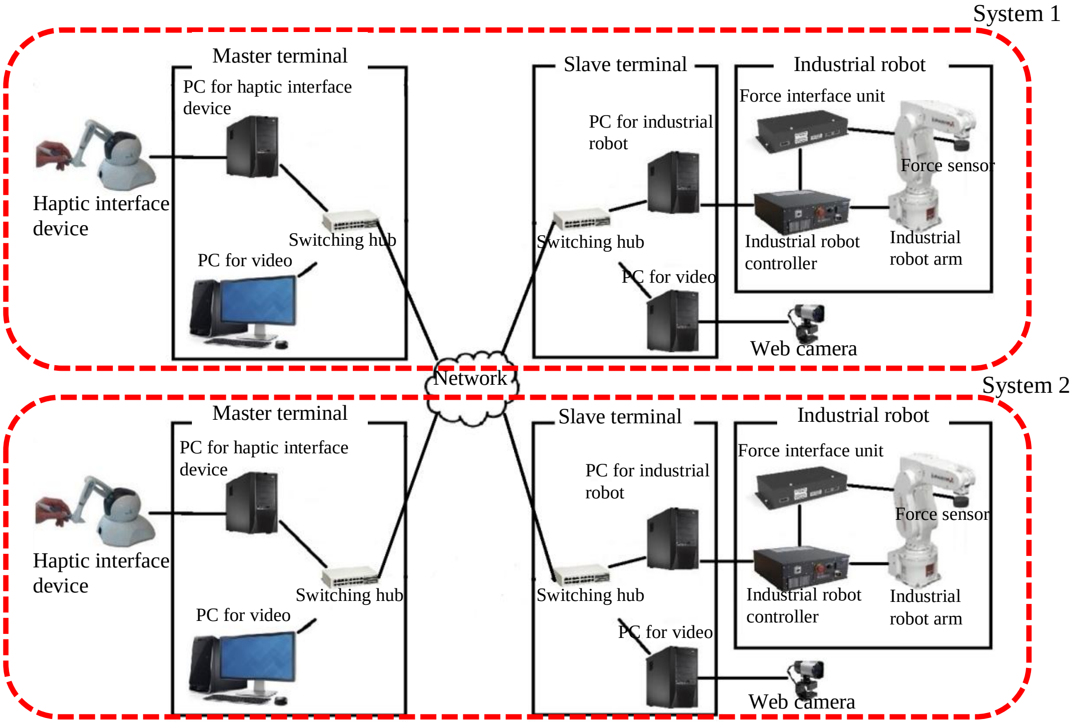

Figure 1. Configuration of two remote robot systems with force feedback.

B. *Remote Operation*

A user at the master terminal can remotely operate the industrial robot arm by using the haptic interface device while watching video. The reaction force outputted through the haptic interface device is calculated from the value sensed by the force sensor as shown in the following equation:

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

where $\mathrm{F}_{\mathrm{t}}^{(\mathrm{m})}$ is the reaction force outputted at the master terminal at time t ($t \geqq 1$), $\boldsymbol{F}_t^{(\mathrm{s})}$ is the force received at the master terminal from the slave terminal at time t, and K_{scale} is a force scale which changes $\boldsymbol{F}_{t-1}^{(\mathrm{s})}$ so as to handle it at the haptic interface device [3]. Also, the position of the industrial robot is calculated as follows:

$$\boldsymbol{S}_t = \begin{cases} \boldsymbol{M}_{t-1} + \boldsymbol{V}_{t-1} & (\text{if } |\boldsymbol{V}_{t-1}| \leqq \boldsymbol{V}_{\max}) \\ \boldsymbol{M}_{t-1} + \boldsymbol{V}_{\max} \dfrac{\boldsymbol{V}_{t-1}}{|\boldsymbol{V}_{t-1}|} & (\text{otherwise}) \end{cases} \tag{2}$$

where $\boldsymbol{S}_t$ is the position vector of industrial robot at time t, $\boldsymbol{M}_t$ is the position vector of haptic interface device at time t. Also, $\boldsymbol{V}_t$ is the velocity vector of industrial robot, and $V_{\max}$ is the maximum velocity of industrial robot ($V_{\max} = 5$ mm/s [3] in this paper).

C. *Cooperation between Systems*

As cooperative work, we handle work in which the two robots carry an object together, or one robot hands the object over to the other robot. In the work, one user or two users located at different places can jointly operate the two robots in which are closely situated. In this paper, we deal with work in which the two robots carry an object together. Because the robot arms are connected to each other by a wooden stick, the control of the systems is multilateral; note that the control of each system is bilateral.

III. Stabilization Control

In this section, we explain the following three types of stabilization control: The reaction force control upon hitting, the stabilization control by viscosity, and the stabilization control with filter.

A. *Reaction Force Control upon Hitting*

The reaction force control upon hitting employs the following calculation method of $\mathrm{F}_{\mathrm{t}}^{(\mathrm{m})}$ instead of Eq. (1):

$$\boldsymbol{F}_t^{(\mathrm{m})} = \begin{cases} K_{\mathrm{scale}}(\boldsymbol{F}_{t-1}^{(\mathrm{m})} + K_i \boldsymbol{F}_{\mathrm{th}}) & (\text{if } |\boldsymbol{F}_{t-1}^{(\mathrm{m})} - K_{\mathrm{scale}}\, \boldsymbol{F}_{t-1}^{(\mathrm{s})}| > |\boldsymbol{F}_{\mathrm{th}}|) \\ K_{\mathrm{scale}}\, \boldsymbol{F}_{t-1}^{(\mathrm{s})} & (\text{otherwise}) \end{cases} \tag{3}$$

where $\boldsymbol{F}_{\mathrm{th}}$ is threshold force ($\boldsymbol{F}_{\mathrm{th}} = 0.003$ N/ms) , $K_i = 1.000 + 0.001i$ ($i \geqq 1$) [6]. 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 $\boldsymbol{F}_{t-1}^{(\mathrm{m})}$ to $K_i \boldsymbol{F}_{\mathrm{th}}$. Otherwise, the calculation method is the same as Eq. (1).

B. Stabilization Control by Viscosity

In the stabilization control by viscosity, the following calculation method of position $S_t^{(m)}$ is employed:

$$\boldsymbol{S}_t = \begin{cases} \boldsymbol{M}_{t-1} + \boldsymbol{V}_{t-1} - C_d(\boldsymbol{M}_{t-1} - \boldsymbol{S}_{t-2}) & (\text{if } |\boldsymbol{V}_{t-1}| \leqq V_{\max}) \\ \boldsymbol{M}_{t-1} + V_{\max}\frac{\boldsymbol{V}_{t-1}}{|\boldsymbol{V}_{t-1}|} - C_d(\boldsymbol{M}_{t-1} - \boldsymbol{S}_{t-2}) & (\text{otherwise}) \end{cases} \quad (4)$$

where C_d is a coefficient related to viscosity. Thus, we produce the viscosity by restricting the movement distance of the industrial robot to some extent. The reason is that viscosity can suppress vibration [12]. In [7], it is shown that the optimum value of C_d is 0.95; we set $C_d = 0.95$ here.

C. Stabilization Control with Filter

Figure 2 shows the block diagram of the stabilization control. The control uses the wave filter in combination with the phase control filter [8]. It can make the remote robot system with force feedback stable against any network delay. For details of the control, the reader is referred to [13] and [14].

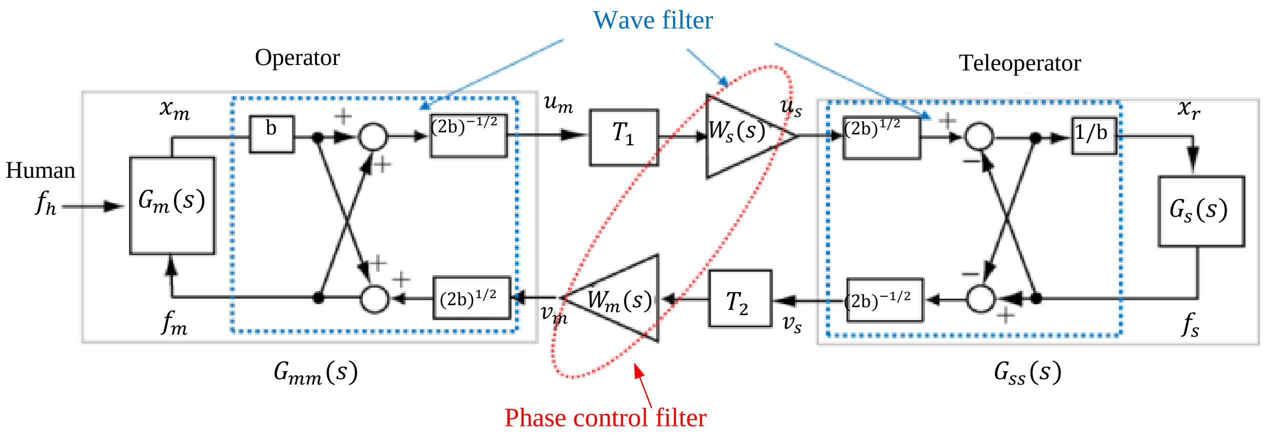

Figure 2. Block diagram of stabilization control with filter.

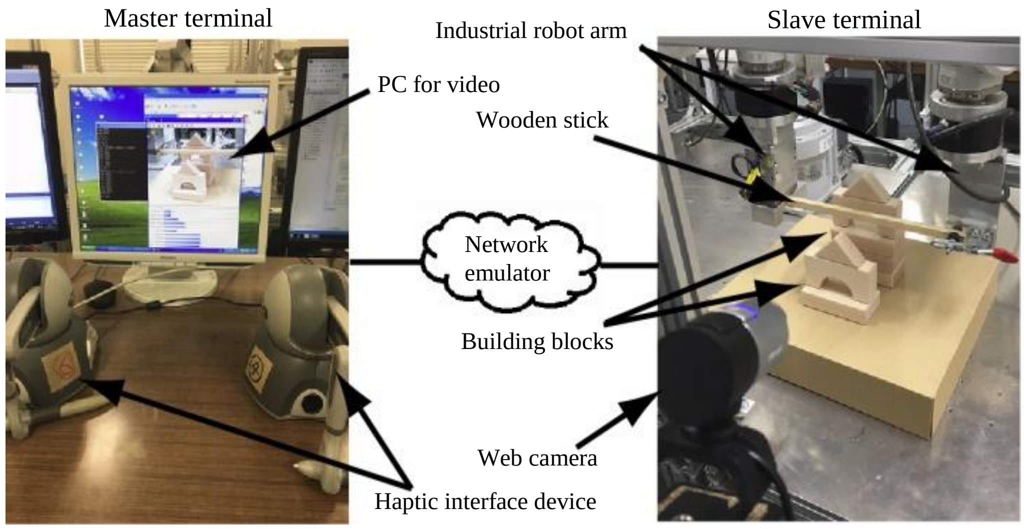

Figure 3. Appearance of system operation.

IV. Experiment Method

We conducted an experiment with the two systems which are shown in Fig. 1. A user remotely operates the two industrial robot arms with the two haptic interface devices of the master terminals by using both hands. To move a wooden stick in almost the same way in the experiment, as shown in Fig. 3, building blocks were piled up front and back of the initial position of the stick before the experiment began. The arrangement of stick and blocks is shown in Fig. 4. The height of the uppermost block on one side differs from that on the other side by 50 mm (see Fig. 3). The user pushed and dropped only the top building blocks with the stick [5]. Also, in order to move the stick at almost the same speed, the user drops the first building block at about 5 second and the second building block at about 15 second. Furthermore, to ensure more stable operation, we disabled the movement of each industrial robot in the left and right direction.

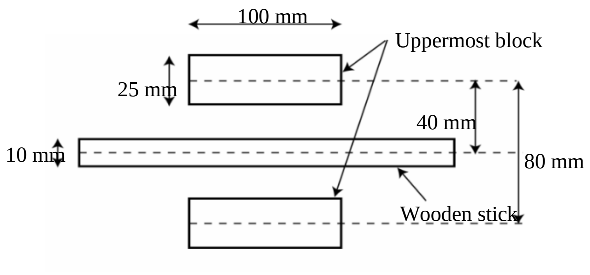

Figure 4. Plane view of arrangement of stick and blocks.

In the experiment, we handled the case where the stabilization control is not carried out as well as the cases where the three types of control are performed. We generated a constant delay (referred to the additional delay) for each packet transmitted between the two terminals by a network emulator (NIST Net [15]) used instead of the network in Fig. 1. Then, we measured the reaction force outputted by the haptic interface device. The ratio of the moving distance of the haptic interface device to that of the industrial robot is 2:1 [8], and the ratio of the force is 1:2.

The reason is that instability phenomena occurred when the ratio of the force was 1:1; to solve the problem is for further study. Also, only one of the two Web cameras was used owing to one user.

V. EXPERIMENT RESULTS

We show the reaction force and position in the front-back direction of the haptic interface device versus the elapsed from the beginning of the experiment in Figs. 5 through 8 under no stabilization control, the reaction force control upon hitting, the stabilization control by viscosity, and the stabilization control with filter, respectively. In the figures, the additional delay is set to 0 ms. Because the reaction force in the up-down direction was almost the same as that in front-back direction, we omitted results in the front-back direction in this paper. Note that the movement of each industrial robot was disabled as described in Section 4. Also, in the case of the stabilization control with filter, we show the reaction force when the additional delay is set to 200 ms, 400 ms, and 800 ms in Figs. 9, 10, and 11, respectively.

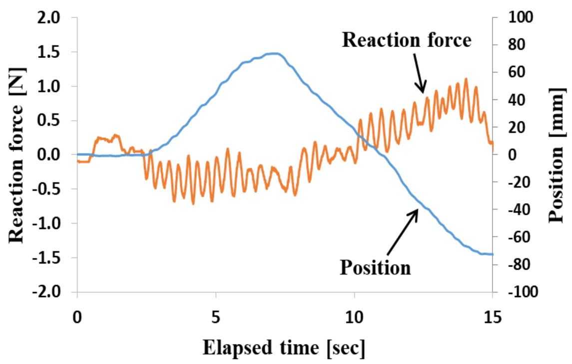

Figure 5. Reaction force and position versus elapsed time under no stabilization control (additional delay: 0 ms).

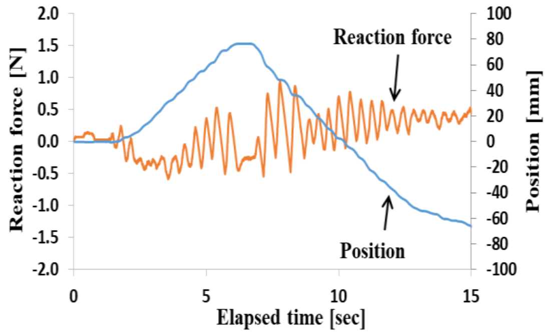

Figure 6. Reaction force and position versus elapsed time under reaction force control upon hitting (additional delay: 0 ms).

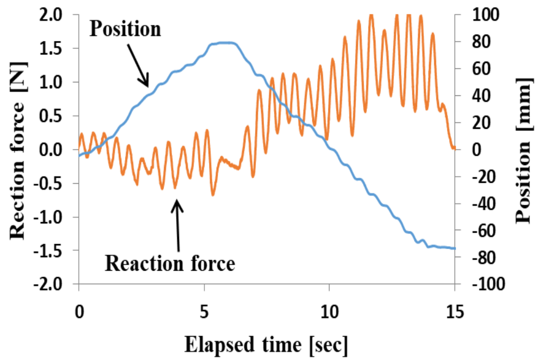

Figure 7. Reaction force and position versus elapsed time under stabilization control with viscosity (additional delay: 0 ms).

From Figs. 5 through 7, we see that when no stabilization control, the reaction force control upon hitting and the stabilization control by viscosity are used, the reaction force greatly vibrates and the position also vibrates slightly. This indicates that the systems are unstable. On the other hand, in Fig. 8, where the stabilization control with filter is used, we notice that the vibrations do not occur. Therefore, we can confirm that it is more difficult to keep the systems stable in this paper than in [4] as described in Section 1.

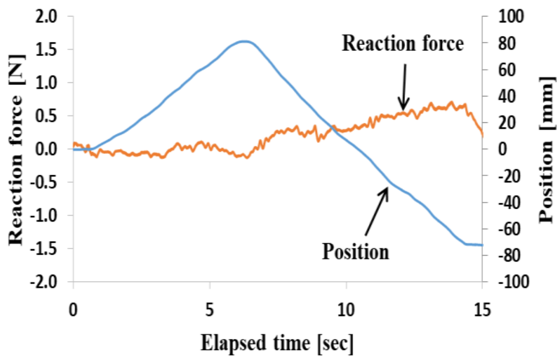

Figure 8. Reaction force and position versus elapsed time under stabilization control with filter (additional delay: 0 ms).

In addition, from Figs. 9 through 11, we find that the reaction force and the position hardly vibrate. This means that the stability is maintained. Also, in each figure, we see that the force at around 6 second starts to increase largely. This is because the position at the time starts to decrease; that is, the moving direction is changed. From Figs. 8 through 11, we observe that the values of the force at around time become larger as the additional delay increases; the absolute values of the force at the other times also become larger. The reason is that the force by viscosity increases as the network delay becomes larger under the control [9].

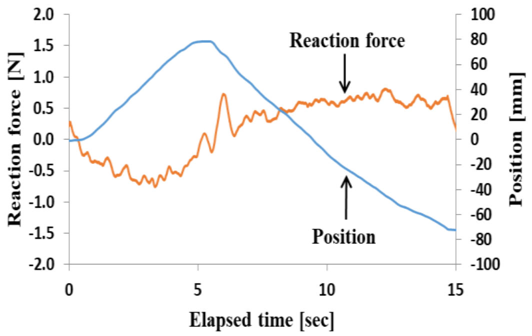

Figure 9. Reaction force and position versus elapsed time under stabilization control with filter (additional delay: 200 ms).

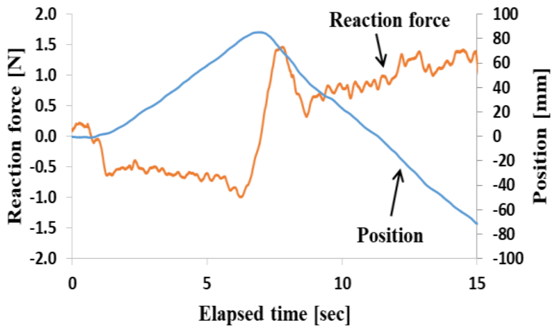

Figure 10. Reaction force and position versus elapsed time under stabilization control with filter (additional delay: 400 ms).

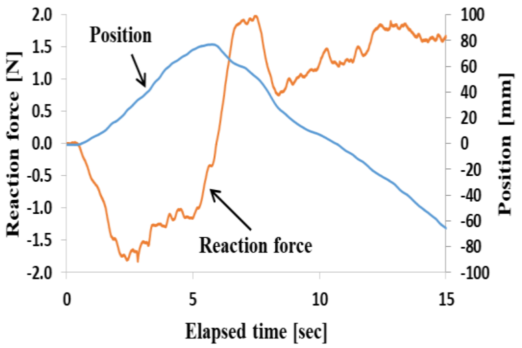

Figure 11. Reaction force and position versus elapsed time under stabilization control with filter (additional delay: 800 ms).

From the above considerations, we can say that the stabilization control with filter is the most effective.

VI. Conclusion

In this paper, we made a comparison of the three types of stabilization control for work of moving one object grasping by robot arms of two remote robot systems with force feedback. One is the reaction force control upon hitting. Another is the stabilization control by viscosity, the other is stabilization control with filter. As a result, we found that the stabilization control with filter is the most effective. We also saw that the reaction force of the other types of control vibrated and the systems were unstable. Furthermore, we noticed that the multilateral stabilization control is more difficult than the bilateral stabilization control; only the stabilization control with filter can be applicable.

In our experiment, one user operated the two haptic interface devices with both hands to carry out the experiment. Because it is also possible that two users perform the experiment in which each user operates a haptic interface devices with one hand. In a preliminary experiment, we found that the work efficiency was degraded more largely compared with operation by one user. As our future work, we will improve the work efficiency.

Acknowledgments

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