Effect of Stabilization Control for Cooperation between Tele-Robot Systems with Force Feedback by Using Master-Slave Relation

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Abstract

By experiment, this paper investigates the effect of the stabilization control with filters to suppress instability phenomena for tele-robot systems with force feedback by using a master-slave relation. As the quality of service (QoS) control to improve the quality of experience (QoE), the systems carry out the adaptive Δ*-causality control, which we previously proposed. In our experiment, we carry a wooden stick together by gripping the two ends of the stick with the two robot arms of the systems. Experimental results illustrate that the stabilization control with filters can suppress instability phenomena.*

Keywords—Tele-Robot System, Remote Control, Force Feedback, Cooperation, Stabilization Control, QoS, Experiment

I. INTRODUCTION

By using multiple bilateral tele-robot (i.e., remote robot) systems with force feedback [1]-[5], we can conduct cooperative work among the systems [6], [7]. This is because a user of such a system can operate a tele-industrial robot having a force sensor via a network by employing a haptic interface device while watching video of the robot motion. By using force feedback for the robot operation, the user can feel the reaction force outputted by the haptic interface device, and he/she can perform more accurate operation. However, if the information about force is transmitted via a network without the quality of service (QoS) [8] guarantee such as the Internet, the quality of experience (QoE) [9] may seriously be degraded and the instability phenomena may occur owing to the network delay, delay jitter, and so on. In order to solve the problems, we need to perform QoS control [8] and stabilization control [10] together.

In [6], the authors investigate the influence of the network delay on cooperative work in which a single user operates the haptic interface devices of the two tele-robot systems with his/her both hands, and carries an object held by the two robot arms. The systems have an equal relationship in this paper, but a master-slave relation between the systems is also important. In [7], thus, the authors conduct the same work as that in [6] by using the tele-robot systems with a master-slave relation and apply the adaptive Δ-causality control [11] to avoid large force applied to the object. As a result, it is illustrated that the control can suppress large force even if the network delay becomes larger. However, to avoid instability phenomena, the reaction force outputted from the haptic interface device is set to a small value by multiplying 0.5 to the force detected by the robot's force sensor. We need to perceive larger reaction force to conduct the work more precisely. To solve the problem, we need to perform the stabilization control with filters [10]. However, the effect of the control has not been clarified quantitatively in the systems using the master-slave relation.

Therefore, in this paper, we perform the stabilization control with filters for the tele-robot systems using the master-slave relation with force feedback in which the adaptive Δ-causality control is exerted. By experiment, we clarify the effect of the stabilization control. We also investigate the effect of the adaptive Δ-causality control under the stabilization control.

The remainder of this paper is organized as follows. In Section II, first we give an outline of the tele-robot systems with force feedback by using the master-slave relation. Next, we explain the adaptive Δ-causality control in Section III, the stabilization control with filters in Section IV, and experiment method in Section V. Then, Section VI presents experimental results and discusses them. Finally, Section VII concludes the paper.

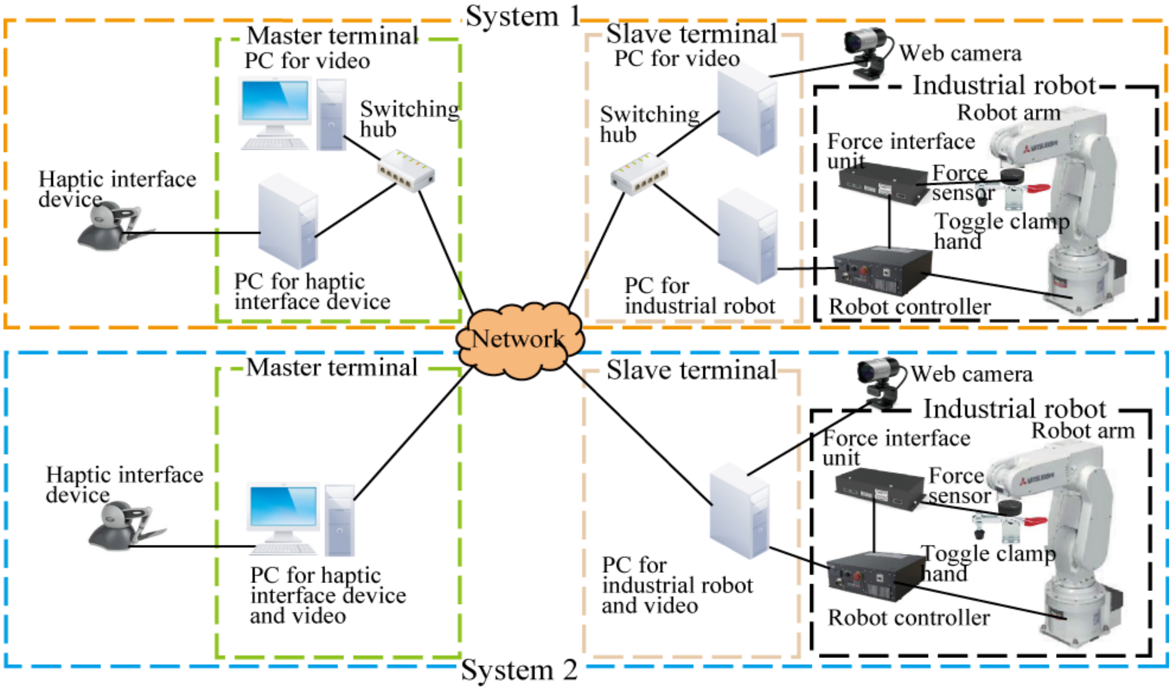


Figure 1. Configuration of tele-robot systems with force feedback.

II. TELE-ROBOT SYSTEMS WITH FORCE FEEDBACK BY USING MASTER-SLAVE RELATION

In this section, we outline the tele-robot systems with force feedback in Subsection II.*A* and how to calculate the reaction force in Subsection II.*B*. We also describe the tele-robot systems by using the master-slave relation in Subsection II.*C*.

A. Tele-Robot Systems with Force Feedback

As shown in Figure 1, each of the two systems (called *systems 1 and 2* here) consists of a master terminal with a haptic interface device (3D Systems Touch [12]), and a slave terminal with an industrial robot and a web camera (made by Microsoft). The master terminal in system 1 is composed of two PCs; one is for haptic interface device, and the other is for video. The two PCs are connected by a switching hub. One PC called PC for haptic interface device and video is used in system 2, and the functions of PC are same as those in system 1. The slave terminal in system 1 also consists of two PCs (called PC for industrial robot and PC for video) which are connected by a switching hub. One PC (called PC for haptic interface device and video) is employed in system 2. PC for industrial robot (or PC for industrial robot and video) is connected to the industrial robot directly by a 100BASE-TX cable. The industrial robot consists of a robot controller (CR750-Q), a force interface unit (2F-TZ561), and a robot arm with 6 DoF (Degree of Freedom) (RV-2FB-Q). The force sensor (1F-FS001-W200) is linked to the tip of the robot arm. Furthermore, a toggle clamp hand is attached to the force sensor. We use the toggle clamp hand to fix an object by a toggle. The reaction force outputted by the haptic interface device is calculated from the value obtained by the sensor (the calculation method will be described in the next subsection).

B. Calculation Method of Reaction Force

The reaction force $\boldsymbol{F}_t^{(\mathrm{m})}$ outputted by the haptic interface device at the master terminal at time t (≥ 1) is calculated by the following equation:

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

where $\boldsymbol{F}_t^{(\mathrm{s})}$ is the force obtained from the slave terminal at time t, and K_{scale} (> 0) is the scaling factor applied to $\boldsymbol{F}_{t-1}^{(\mathrm{s})}$. In this paper, we set $K_{\mathrm{scale}} =$ 1.0 (note that $K_{\mathrm{scale}} = 0.5$ in [7]).

Furthermore, the position vector $\boldsymbol{S}_t$ of the industrial robot at time t (≥ 2) can be obtained from the following equation:

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

where $\boldsymbol{M}_t$ is the position vector of the haptic interface device that the slave terminal receives from the master terminal at time t, and $\boldsymbol{V}_t$ is the velocity vector of the robot arm at time t. $V_{\max}$ is the maximum moving velocity, and the moving amount is limited so that the robot does not move too fast. In this paper, we set $V_{\max} = 5$ mm / s [13].

C. *Master-Slave Relation*

The two tele-robot systems in Subsection II.*A* are used as follows. One system is master, and the other is slave. The robot of the slave system (called the slave robot here) works according to the movement of the robot of the master system (called the master robot). Position information of the master robot is transmitted from the slave terminal of the master system to the slave terminal of the slave system, and the slave robot is controlled by using the information (i.e., unilateral control). For simplicity, the position information of the haptic interface device of the slave system is not transmitted to the slave terminal. A user of the master system operates the haptic interface device of the master system, and another user of the slave system can feel the reaction force by holding the haptic interface device of the slave system.

III. ADAPTIVE Δ-CAUSALITY CONTROL

When the network delay between the master and slave systems is large, the slave robot lags behind the master robot in the movement of robot arm. Then, the force applied to an object carried by the two robot arms becomes larger, and the operability of the haptic interface device is significantly degraded. We reduce the force and improve the operability by carrying out the adaptive Δ-causality control [10], which delays the output timing of the robot's position information dynamically according to the network delay; by this, because we can delay the master robot's operation by the network delay from the slave terminal of the master system to the slave terminal of the slave system, the operations at both robots are performed at almost the same time.

The adaptive Δ-causality control outputs position information at the generation time (i.e., the timestamp) + Δ (> 0) seconds if the information is received by the time + Δ. Otherwise, the information is discarded as old and useless information to keep the causality. The minimum value Δ_{L} and the maximum value Δ_{H} ($\Delta_{\mathrm{H}} \geq \Delta_{\mathrm{L}} > 0$) are set for Δ. Also, since Δ

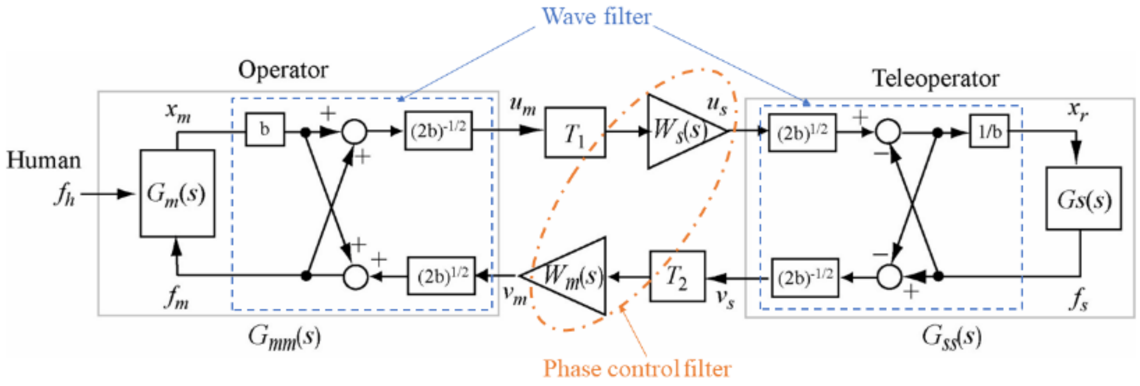
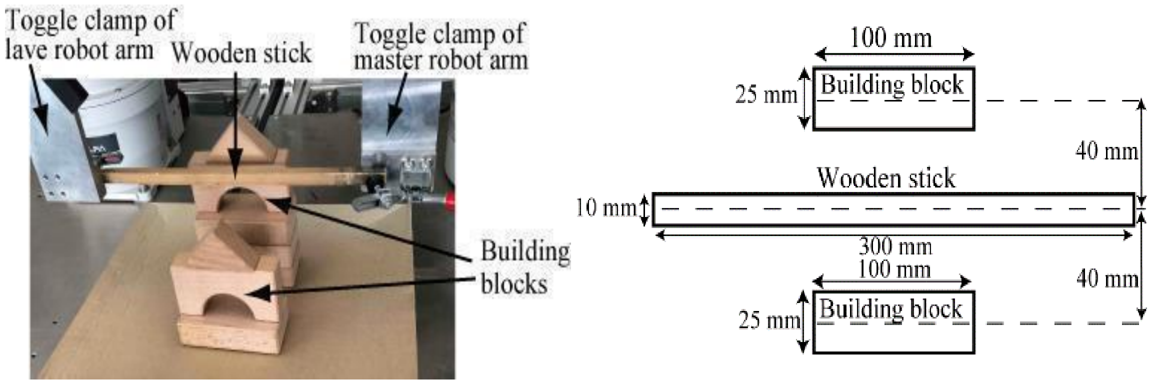


Figure 2. Block diagram of stabilization control with filter.



(a) Displayed image of video.

(b) Plan view

Figure 3. Positional relationships between wooden stick and building blocks.

changes dynamically according to the network delay, the value D_t $(t \geq 0)$ obtained by smoothing the network delay d_t measured at time t by the following equation is used as Δ:

$$\begin{cases} D_0 = d_0 \\ D_t = \alpha D_{t-1} + (1 - \alpha) d_t \ (t \geq 1) \end{cases} \quad (3)$$

where α is a smoothing coefficient, and we set α = 0.998 [15] in this paper.

IV. STABILIZATION CONTROL

This section gives an outline of the stabilization control with filters. Figure 2 shows the block diagram of the stabilization control. The control employs the wave filter in combination with the phase control filter [10], [15]. It can make the tele-robot systems with force feedback stable for any network delay. The reader is referred to [10], [15], and [16] for details of the control.

V. EXPERIMENT METHOD

In this paper, for simplicity, the experiment was performed by one person, and the video was watched only at the master system. In the experimental system, the master and slave systems were connected via a network emulator (NIST Net [17]), and a constant delay was added to each packet transferred in both directions between the two slave terminals (the one-way constant delay is called the additional delay here). The additional delay between the master and slave terminals in each system was 0 ms for simplicity.

In the experiment, in order to move the robot arms in almost the same way always, we carried out work of pushing the top block piled up front and behind the initial position of the wooden stick held by the two toggle clamp hands of the robot arms for about 15 seconds (it took about 5 seconds to drop the front block, and around 10 seconds to drop the behind block. Note that the hands change the movement directions after dropping the front block). Figure 3 shows the positional relationships between the wooden stick and building blocks; the position difference between the front and behind brocks is 80 mm. The height of the behind block is 50 mm higher than the front block as shown in Figure 3 (a). In order to realize more stable operation, the motion of the robot arm in the left and right (the *y*-axis) direction was stopped, and the motion was performed only in the front and behind (the *x*-axis) and up and down (the *z*-axis) directions [6].

We changed the additional delay between the two robots of the master and slave systems to 0 ms and 200 ms with and without the adaptive Δ-causality control (called *control* and *no control*, respectively, in Section VI). Then, we measured the position and the force detected by the force sensor.

VI. EXPERIMENTAL RESULTS

We show the position and force of each robot's x and z axes as a function of the elapsed time from the beginning of the work in Figures 4 and 5. We set the additional delay to 200 ms in the figures.

In Figures 4 and 5, we see that there is no instability phenomenon in the tele-robot systems even though the reaction force output from the device is multiplied by 1.0 to the force detected by the robot's force sensor (K_{scale} = 1.0). However, instability phenomena (i.e., large vibrations) of the robot arms occurred and we could not carry out the work when we did not carry out the stabilization control; even if the additional delay is 0 ms, the phenomena occurred. Thus, we do not show the position and force in this case. On the other hand, we confirmed that there was no instability phenomenon under the stabilization control with filters when the additional delay is less than or equal to at least 400 ms; we obtained almost the same results as those in Figures 4 and 5. Therefore, we can say that the instability phenomena of the robot arms are greatly suppressed by the stabilization control.

We find in Figures 4 and 5 that the position and force of no control fluctuate greatly, but those of control are suppressed. In Figures 4 (a) and (c), we observe that the position of the salve robot is about 200 ms behind that of the master robot. However, we confirm in Figures 5 (a) and (c) that the two positions are almost the same. These are the effects of the adaptive Δ-causality control under the stabilization control.

Furthermore, from Figures 4 and 5, we can confirm that the movement direction of the robot is reversed at about 6 second, and the sign of the force is also reversed. This is because the direction of movement to drop the behind block after dropping the front block is changed at about 6 second. Figures 4 and 5 reveal that the force in *x*-axis is larger than the force in *z*-axis under control, but the magnitudes of force in the x-axis and *z*-axis directions are almost the same under control.

VII. CONCLUSION

In this paper, we applied the stabilization control with filters for cooperative work between the tele-robot systems with force feedback by using a master-slave relation. As QoS control, we carried out the adaptive Δ-causality control, and we also investigated the effect of the stabilization control. As a result, we found that the instability phenomena can greatly be suppressed by the control in the systems. We also saw that the adaptive Δ-causality control is effective under the stabilization control.

As our future work, we will apply the stabilization control with filters and the adaptive Δ-causality control to the systems with an equal relationship and investigate their effects. We will also switch the master-slave relationship dynamically according to the network delay in the systems.

ACKNOWLEDGMENT

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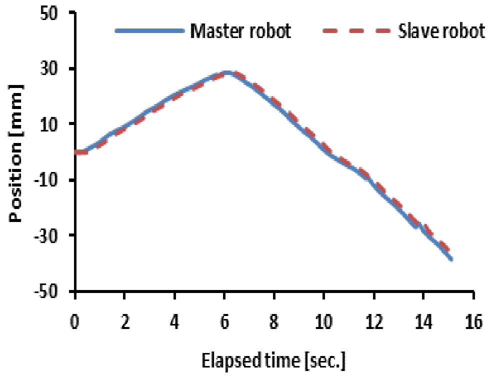
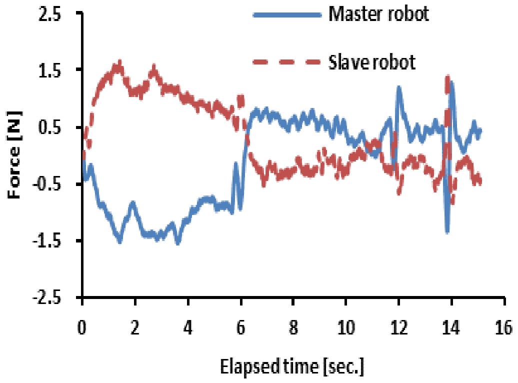
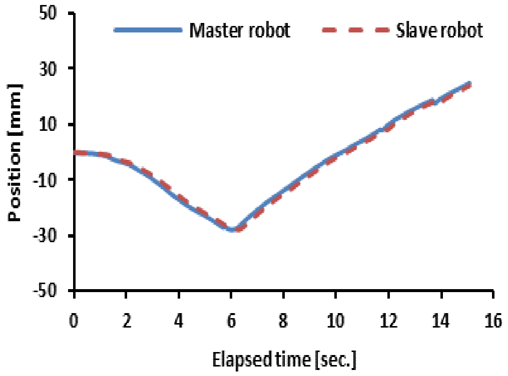


(a) Position of *x*-axis



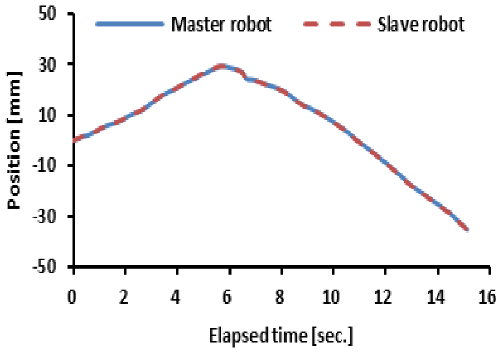
(b) Force of *x*-axis



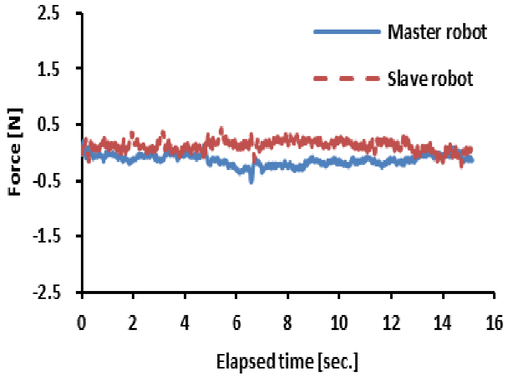
(c) Position of *z*-axis

(d) Force of *z*-axis

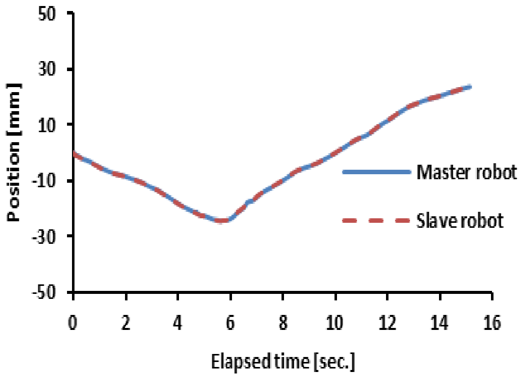
Figure 4. Robot position and force vs. elapsed time under no control (additional delay: 200 ms).



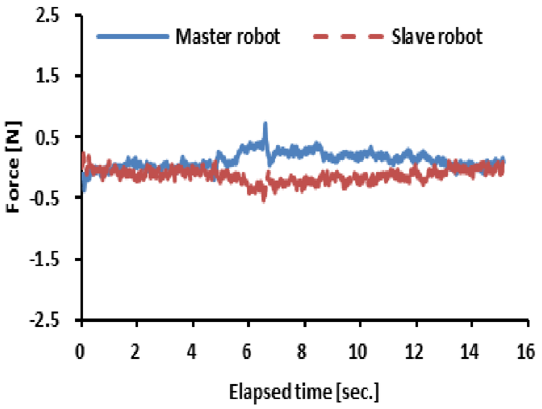
(a) Position of *x*-axis



(b) Force of *x*-axis



(c) Position of *z*-axis



(d) Force of *z*-axis

Figure 5. Robot position and force vs. elapsed time under control (additional delay: 200 ms).