Network Delay Mitigated Remote Robot Control with Force Feedback for Improved QoS

QoS向上のための力覚フィードバックを用いたネットワーク遅延緩和型遠隔ロボット制御

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Contents

Chapter 1

Introduction

The research interest in remote robot control has been exponentially increasing over the recent years [1]-[17]. Remote robot control systems find their applications from manufacturing units in industries [15] to intensive care units in hospitals [16]. Traditionally, tele-operation has been employed in complex safety-critical applications where it would be extremely dangerous and hazardous for human to complete an operation. The evolution of tele-operation has created advanced tele-presence systems where each user can really perceive his/her presence in the tele-operation site. In a teleoperation system, the commands from the user are transmitted to the remotely-located robot via a communication network. With the addition of force feedback and rapid development in haptic technology, the accuracy and efficiency of teleoperation can be increased tremendously. The inclusion of force feedback enables the user to perceive the force exerted at the remote robot.

Recently, researchers have been showing keen interests towards cooperative remote robot systems [18]-[27]. With multiple remote robot systems working together, the possibility of the applications are endless. For example, in factories, using multiple remote robot systems to perform a cooperative task of carrying an object is more efficient than using a single system. When two systems are working together on a cooperative task, the robots should move by the same distance and angle at the same time to perform the given task smoothly. In other words, the robots should be synchronized spacially and temporally. Therefore, for multiple remote robot systems with force feedback, spatial and temporal synchronization among the systems are necessary to ensure better collaboration and efficient operation. However, when control information is transmitted via a communication network, the network delay, delay jitter, and packet loss should be kept as small as possible for performing smooth operation [28]-[43]. When the remote robot systems are used over a communication network that does not guarantee QoS (Quality of Service

[73]-[75]), spatial and temporal synchronization between the systems can largely be degraded owing to unfavorable network conditions. Moreover, when remote robot systems with force feedback are engaged to perform a cooperative task of carrying an object, the object may be subjected to large force due to the lack of spatial and temporal synchronization, which is caused by the network delay, delay jitter, and packet loss. The object may seriously be damaged due to the large force and may cause instability [88]. To avoid this, it is essential to study the influences of different unfavorable network conditions and to employ efficient QoS control [76]-[78] and stabilization control [79]-[85].

In this thesis, we specially concentrate on QoS control to mitigate the influence of network delay in remote robot systems with force feedback. We investigate the influence of network delay in the remote systems with force feedback by performing the task of carrying an object. Then, based on experimental results, we clarify which QoS control should be employed for achieving proper synchronization and to keep operability high.

In this chapter, we describe remote robot control in Subsection 1.1. We explain force sense in Subsection 1.2. We elaborate remote robot systems with force feedback in Subsection 1.3. Quality of Service (QoS) is discussed in Subsection 1.4. A brief explanation about QoS control is presented in Subsection 1.5. Section 1.6 provides a brief explanation about the stabilization control. The purpose and the organization of this thesis are explained in Subsection 1.7.

1.1 Remote robot control

Remote robot control enables a user to manipulate a remotely located robot by sending commands/instructions through a communication network. The user acts as master that controls the remote robot which is the slave. With advancement in technology such as haptics, the user can perceive the force exerted at the object which is handled by remote robot. In a remote robot system, the user at the master terminal can use a haptic inteface device to engage the remote robot at the slave terminal while viewing video.

1.2 Force sense

1.2.1 Characteristics of force sense

Force sense is related to the reaction force that we feel when we touch an object. The user can feel his presence at the remote location with force sense in addition to auditory and visual senses. To reproduce the natural feel of touch through the interface device, the update rate for the haptic media should be higher than for auditory and visual senses. The update rate for the haptic media is 1 khz or higher [56], which is much larger than that of visual media. This higher update rate makes it susceptible to unfavorable network conditions such as network delay, packet loss and delay jitter [44]-[49]. The maximum allowable delay for the haptic media is about 30 to 60 ms [49], while for the auditory media it is about 400 ms [50].

1.2.2 Haptic interface devices

The haptic technology has been widely used in telerobotics for facilitating force sense [51]-[55]. The word "haptics" is derived from "haptesthai", a word for senses related to touch in the Greek language. Haptic interface devices are devices that deliver haptic information to the user [56]-[60]. There are various types of haptic interface devices according to how the sense of touch is presented to the user. The most common haptic interface devices are the devices that is operated by hand or attached to hand [57]. The haptic interface devices ranges from a simple haptic gloves to a complex wearble exoskeleton. Some of widely recognized examples of haptic interface devices are 3D Systems Touch [61], 3D Systems Touch-X [62], Phantom Premium [63], Omega.X [64], Virtuose [65], SPIDAR-G [66], Falcon [67], Wolverine [68], and so on.

We have used 3D Systems Touch (see Fig. 1.1) for experiments mentioned in this thesis. This device provides compact force feedback interface with dimensions 6.4 inches in width, 4.8 inches in height, and 2.8 inches in depth. It has 3 DoF force feedback and 6 DoF positional sensing. The maximum exertable force is 3.3 N [61].

Figure 1.1: Example of haptic interface device (3D Systems Touch).

1.3 Remote robot system with force feedback

1.3.1 System configuration

The system configuration for remote robot system with force feedback is as shown in Fig. 1.2. The System is comprised of the master terminal and the slave terminal. The master terminal is composed of two PCs: One for the haptic interface device and the other for the video. The PC for haptic interface device and PC for video are connected to each other by using a switching hub. A haptic interface device (3D Systems Touch [61]) is connected to PC for haptic interface device. The slave terminal consists of PC for industrial robot and PC for video, which are connected to each other by using a switching hub. An Ethernet cable (100 BASE-TX) is used to connect the PC for industrial robot and the industrial robot. The industrial robot consists of a robot arm (RV-2F-D [70] by Mitsubishi Electric Corp.), a robot controller (CR750-D) [70], and a force interface unit (2F-TZ561) [71]. A force sensor (1F-FS001-W200) [71] is fitted to the robot arm. A toggle clamp is attached to the force sensor to carry objects for performing cooperative work.

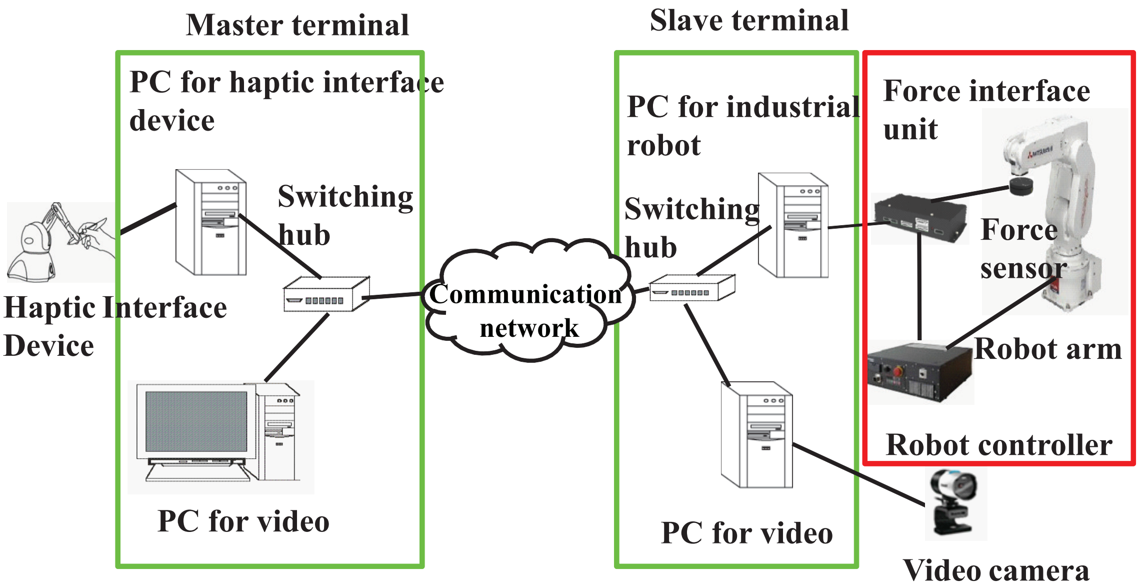


Figure 1.2: Configuration of remote robot system with force feedback.

1.3.2 Remote operation

A user can use the haptic interface device to remotely operate the industrial robot while viewing video. The initial position of the haptic interface device corresponds to the initial position of the industrial robot. At the master terminal, the PC for haptic interface device receives the position information of the haptic interface device every millisecond. The position information is transmitted to the PC for industrial robot at the slave terminal by using UDP (User Datagram Protocol) [100]. The PC for industrial robot uses the real-time control function and real-time monitor function [72] every 3.5 milliseconds to get the position and force information from the industrial robot. At the master terminal, the PC of haptic interface device receives the position and force information transmitted from the slave terminal.

1.3.3 Position calculation

At the slave terminal, the position vector of the industrial robot $\boldsymbol{S}_t$ at time t $(t \geq 1)$ is calculated as follows:

$$\boldsymbol{S}_t = \begin{cases} \boldsymbol{M}_{t-1} + \boldsymbol{V}_{t-1} & (\text{if} V_{\text{max}} \geq |\boldsymbol{V}_{t-1}|) \\ \boldsymbol{M}_{t-1} + V_{\text{max}} \frac{\boldsymbol{V}_{t-1}}{|\boldsymbol{V}_{t-1}|} & (\text{otherwise}) \end{cases} \tag{1.1}$$

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 vector of the robot arm at time t. V_{max} is the maximum moving velocity, and we set V_{max} = 5 mm/s in this study [86].

1.3.4 Force calculation

The reaction force at the master terminal $\boldsymbol{F}_t^{(\text{m})}$ outputted through the haptic interface device at time t $(t \geq 1)$ is calculated as follows:

$$\boldsymbol{F}_t^{(\text{m})} = K_{\text{scale}} \boldsymbol{F}_{t-1}^{(\text{s})} \tag{1.2}$$

where $\boldsymbol{F}_t^{(\text{s})}$ is the force received from the slave terminal at time t and K_{scale} is the force scaling factor. The reaction force enables the user to perceive the force exerted on the industrial robot at the slave terminal and facilitates force feedback.

1.4 Quality of Service (QoS)

The International Telecommunication Union (ITU) defines Quality of Service (QoS) as "collective effect of service performances which determine the degree of satisfaction of a user of the service" [73]. QoS indicates how good the performance of a service is. To measure QoS quantitatively, we use QoS parameters. Some of the QoS parameters for communiation networks are delay , jitter, packet loss, bitrate, frame rate and throughput [74]. To keep the QoS high, we should study how these parameters affect a particular service and apply QoS control to mitigate the deterioration of quality.

When remote robot control is used over a communication network that does not guarantee QoS such as the Internet, the QoS may seriously degrade owing to network delay, delay jitter, and packet loss. Hence, it is important to study the influence of various network conditions and employ efficient QoS control.

1.5 QoS control

A number of researchers have proposed various types of QoS control for remote robot control systems with force feedback. As QoS controls, in this thesis, we will be discussing the adaptive Δ-causality control and the robot position control with force information.

1.5.1 Adaptive Δ-causality control

For a cooperative work, it is essential for robots to move synchronously. If the robots are not moved at the same time, a large force may be applied to the object carried by the robots. This large force can seriously damage the object. The adaptive Δ-causality control [95] dynamically adjusts the output timings of the position information of the robots in accordance with the network delay, so as both the robots move at the same time to achieve high operability and to mitigate the force exerted to the object carried by the robots.

In the adaptive Δ-causality control, the position information is outputted at a generation time + Δ ($\Delta > 0$) seconds if it is received by the time + Δ to maintain causality. The information is discarded if it is received after that particular time. The maximum value Δ_{H} and minimum value Δ_{L} ($\Delta_{\mathrm{H}} \geq \Delta_{\mathrm{L}} > 0$) are set for Δ. The value of Δ is dynamically changed in accordance with the network delay measured at some intervals.

1.5.2 Robot position control with force information

The robot position control with force information [92] employs the relation between the robot position information and force to dynamically adjust the robot position to reduce the force applied to an object carried by the robots. In this QoS control, a position adjustment vector $\boldsymbol{P}$ is added to position $\boldsymbol{S}_t$ to obtain the new position vector $\hat{\boldsymbol{S}}_t$ of the robot. The difference in the position between the two robot arms is decreased by the position adjustment vector $\boldsymbol{P}$. In other words, the robot arm is moved by $\boldsymbol{P}$ in the direction so as to abate the large force exerted to the object carried by the robot arms.

1.6 Stabilization control

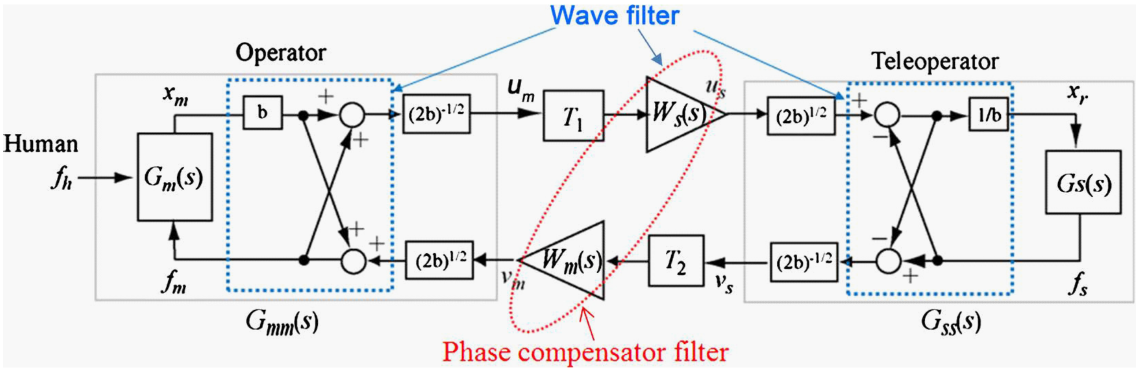


Figure 1.3: Stabilization control with filters.

There are various types of stabilization control used to reduce the instability problem in remote robot system with force feedback [79]-[84]. In this thesis, the stabilization control with filters [84] is applied to stabilize the system. Figure 1.3 shows the block diagram of the filter-based stabilization control. This control applies a combination of the wave filter and the phase compensator filter. The transfer functions of the master and the slave terminals are depicted as G_m(s) and G_s(s), respectively. The force information sent to the master terminal from the slave terminal is denoted as f_s and the output force for the master terminal is represented as f_m. The force exerted from the user at the master terminal is given by f_h. The position vectors at the master and slave terminals are indicated as x_m and x_r, respectively. This control ensures stable force feedback up to a network delay of around 800 ms [85].

1.7 Purpose and organization of this thesis

In a remote robot system with force feedback, we can manipulate a remotely located robot by using a haptic interface device while viewing video. With multiple remote robot systems, various types of cooperative work can be performed. However, when the network delay increases, the spatial and temporal synchronization between the systems may deteriorate significantly. To solve this problem, we have to study the influence of network delay and employ efficient QoS control. In this study, we focus on the influence of network delay and effects of various types of QoS control on remote master-slave robot systems and remote robot systems with force feedback using peer-to-peer relation.

In the remote master-slave robot systems, one system acts as master and other as a slave. An operator of the master system uses the haptic interface device to move both the robots cooperatively while watching video. For a cooperative work in which an object is carried by two remote robots together, spatial and temporal synchronization between robots is important to keep the operability high. In [91], the authors have investigated effects of the adaptive Δ-causality control and showed that the influence of network delay in the remote master-slave systems has been significantly mitigated by using the control. In [92], the robot position control with force information is proposed to minimize large force that is applied to an object by adjusting the robot position finely in the direction to minimize the force in cooperative work for the case of equal relation between robots. In this thesis, we compare effects of the adaptive Δ-causality control and robot position control with force information in the remote master-slave robot systems. We also examine the effect of a combination of the adaptive Δ-causality control and the robot position control with force information in the systems to find out which type of QoS control is the most effective.

For remote robot systems with force feedback using peer-to-peer relation, we propose the local and global adaptive Δ-causality control to mitigate influences of network delay in two remote robot systems with force feedback using peer-to-peer relation for cooperative work. In the local adaptive Δ-causality control, the adaptive Δ-causality control is carried out between two robots, or between a haptic interface device and a robot in each system. In the global adaptive Δ-causality control, the adaptive Δ-causality control is applied to both between the robots, and between the haptic interface device and robot of each system.The effects of the local adaptive Δ-causality control between robots, local adaptive Δ-causality control between device and robot, and global adaptive Δ-causality control is compared to find the best control among the three by experiment.

The remainder of the thesis is structured as follows. In Chapter 2, we examine the influence of network delay in remote master-slave robot systems [101]. From the experimental results, we find that as the network delay becomes larger, the average work time, the average force of robots, and the average reaction force at the haptic interface devices increase. Larger force makes the system unstable and difficult to operate. This results in degradation of operability, that is Quality of Experience (QoE) [75]. As a result, we conclude that to eradicate this problem, it is vital to perform QoS control to achieve efficient operation during unfavorable network conditions.

In Chapter 3, we study the effects of the adaptive Δ-causality control and robot position control with force information in the remote master-slave robot systems to reduce the influence of network delay [102]. We find that the position difference between master and slave robots increases, as the network delay becomes larger. This results in larger force exerted on the object carried by the robots. In the adaptive Δ-causality control, the output timing of the position information of the master robot is adjusted dynamically to reduce the difference in position between the robots to achieve smooth completion of work. In the robot position control with force information, the robot position is changed to reduce the force exerted on the object. We also clarified the effects of a combination of both types of control. Based on the experimental results, we find that a combination of both types of control is the most effective.

In Chapter 4, we propose the global and local adaptive Δ-causality control to alleviate the influence of network delay in the remote robot systems with peer-to-peer relation [103]. The global adaptive Δ-causality control dynamically changes output timing of the position of each robot according to the network delay between robots, and in each system to reduce the difference in position between the robots. The local adaptive Δ-causality control between the robots dynamically changes the output timing of each robot according to the network delay between the robots, while the local adaptive Δ-causality control between the haptic interface device and the robot involves dynamically changing output timing of the position at each robot in accordance with the network delay in each system to minimize the position difference. By experiment, we also compare the effects of the global and local adaptive Δ-causality control. Based on the experimental results, we illustrate that the global adaptive Δ-causality control is better than the local adaptive Δ-causality control.

Finally, the summary and conclusion of this thesis are presented in Chapter 5. We also suggest future directions and challenges based on the results of this study.

Chapter 2

Influences of network delay in remote master-slave robot systems with force feedback

2.1 Introduction

As described in Chapter 1, researchers have been actively involved in using multiple remote robot systems collaboratively to perform cooperative work [18]-[27]. With two or more remote robot systems with force feedback working together, the efficiency and accuracy of the cooperative work can be increased tremendously. Spatial and temporal synchronization between systems is essential to perform an efficient cooperative work. On the other hand, when the force information is transferred over a communication network with poor quality of service (QoS) [73] like the Internet, the quality of Experience (QoE) [75] may seriously be degraded owing to the network delay, delay jitter, and packet loss. To carry out QoS control which avoids the degradation efficiently, the influences of network delay, delay jitter, and packet loss should be clarified.

The influences of network delay in the remote robot systems have actively been studied in [86]-[88]. In [86], it is clarified that the average work time increases with the network delay. In [87], it is shown that the average work time increases with the network delay in an experiment where a user delivers an object to and receives from the robot by using a single remote robot system. In [88], the influence of the network delay in cooperative task between the two remote robot systems using the peer-to-peer relation is investigated. In the peer-to-peer relation, the two remote robot systems act as independent systems working together to complete a given task. As another relation, we have the master-slave relation. In the master-slave relation, one system acts as the master and the other as the slave to perform a task. The peer-to-peer relation and master-slave relation between the systems can be applied in accordance with the network conditions. When the network delay of one system becomes larger, the other system with the better network condition can act as the master and continue the cooperative work smoothly, especially for real-time safety-critical applications such as tele-surgery. The peer-to-peer relation can be used when we need two independently-operating systems working together.

The influence of network delay for remote master-slave robot systems has not been clarified so far. Therefore, in this chapter, we examine the influence of network delay in the remote master-slave robot systems with force feedback. We clarify the influence of network delay by carrying out cooperative work of moving a wooden stick grasped by two robot arms together.

The remaining sections of this chapter is structured as follows. Section 2.2 elaborates the remote robot system with force feedback. Section 2.3 describes the experiment method. We present experimental results in Section 2.4. Finally, Section 2.5 presents the summary of the chapter.

2.2 Remote master-slave robot systems

2.2.1 System configuration

The configuration of the remote robot system with force feedback is shown in Fig. 2.1. The experimental setup comprises of the two remote robot systems (referred to as *systems 1* and *2* here). Each remote robot system consists of the master terminal and the slave terminal. The master terminal is composed of a haptic interface device (3D Systems Touch [61]), PC for the haptic interface device and PC for video. A switching hub is used to connect the PC for haptic interface device and the PC for video. The slave terminal consists of PC for the industrial robot and PC for video. The two PCs are connected to each other by using a switching hub. An Ethernet cable (100 BASE-TX) is employed to connect PC for industrial robot and the industrial robot directly. The industrial robot consists of a robot arm (RV-2F-D by Mitsubishi Electric Corp.), a robot controller (CR750-D),and a force interface unit (2F-TZ561). A force sensor (1F-FS001-W200) is appended to the robot arm. The robot arm of system 1 has an electric hand (see Fig. 2.2), and that of system 2 has a toggle clamp hand (see Fig. 2.3).

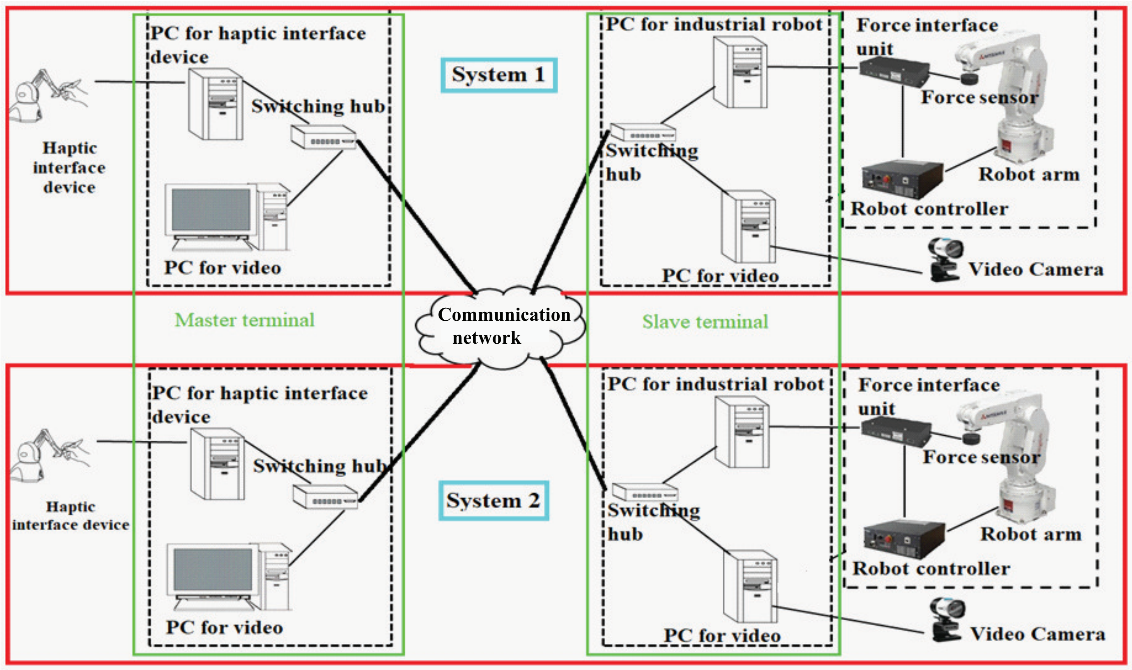


Figure 2.1: Configuration of remote robot systems with force feedback.

2.2.2 Remote operation

A user can use the haptic interface device at the master terminal to manipulate the industrial robot at the slave terminal while viewing video. PC for the haptic interface device at the master terminal inputs the position information from the haptic interface device. The position information is transmitted to PC of the robot arm at the slave terminal. The industrial robot at the slave terminal gets the position and force information of its robot arm by employing the real-time control function and real-time monitor function [70]. Then, PC for the industrial robot sends the inputted force information of the robot arm to PC for the haptic interface device at the master terminal.

2.2.3 Master-slave relation

In the master-slave relation, the industrial robot of system 1 acts as the master, and that of system 2 does as the slave. The movement of the robot arm of system 1 is followed by the robot arm of system 2 to improve the work efficiency. A user of the master robot manipulates the haptic interface device to move both robots cooperatively while watching video. The user of the slave robot just holds the haptic interface device while perceiving the force in our experiment described later. We do not send the position information from PC for the haptic interface device to PC for the robot in system 2.

In system 1, which has the master robot, PC for the haptic interface device of the

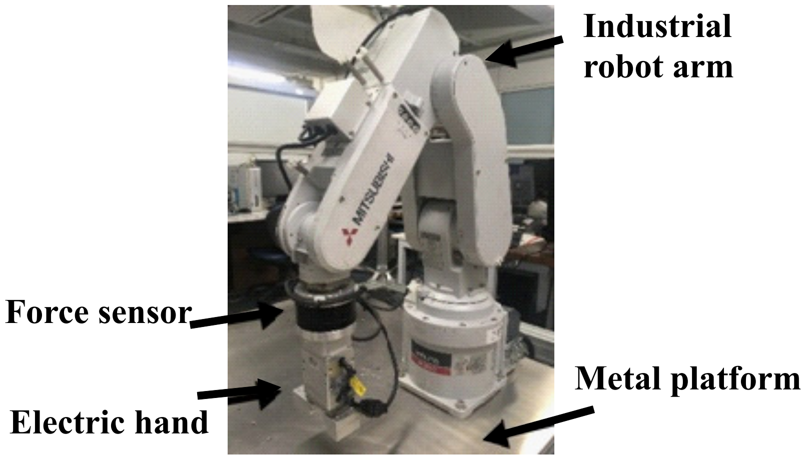


Figure 2.2: Industrial robot arm with electric hand.

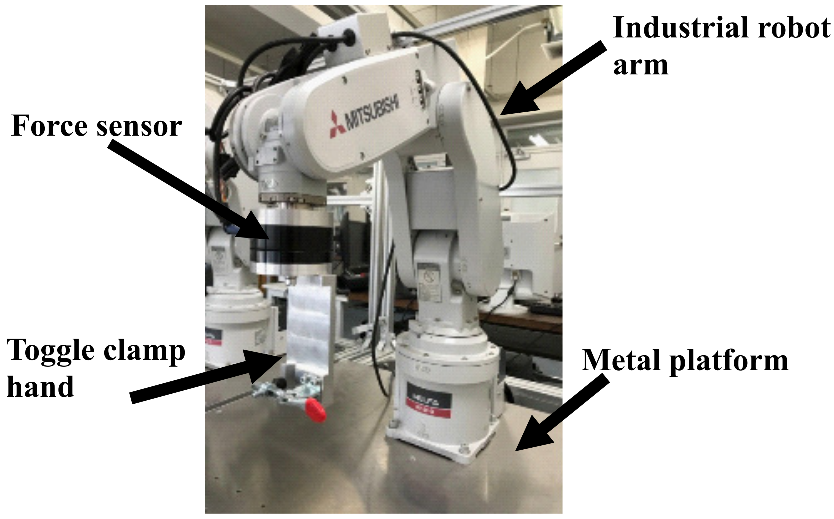


Figure 2.3: Industrial robot arm with toggle clamp hand.

master terminal sends the position information to PC for the industrial robot. Then, the position information is sent from PC for industrial robot in system 1 to PC for industrial robot in system 2. PC for the robot in system 2 controls the robot by using the information, thereby enabling cooperative movement using the master-slave relation. When the network delay between the two PCs for the industrial robots is small, the operability remains good. However, when the network delay increases, the operability may deteriorate largely. Therefore, the influence of the network delay on cooperative work using the master-slave relation should be examined.

2.3 Experiment method

To investigate the influence of network delay between the two PCs for the industrial robots, we carried out a task of pushing and dropping wooden building blocks with wooden stick grasped by the two robots. The wooden blocks are arranged before and behind the wooden stick (width: 10 mm × height: 10 mm × length: 300 mm) which is held by the master and slave robot arms as shown in Fig. 2.4.The top plane view of the arrangement is shown in Fig. 2.5. The task is to push and drop the uppermost blocks of the arranged building blocks (front and back) with the wooden stick held by the master and slave robot arms by using the haptic interface device of the system 1 while watching video. The force mapping ratio [4] between the haptic interface device and the robot in each system is set to 1:5 (determined by a preliminary experiment), and the spatial mapping ratio is set to 1:1 [87]. The robot arm of each system is allowed to move in front and back, and up and down directions. The movement in left and right direction is restricted for simplicity.

The task of pushing and dropping the uppermost wooden blocks was carried out for different network delays between the two PCs for the industrial robots. The network delay was increased between the master and slave robots by using a network emulator (NIST Net [89]). The increased delay is called as the additional delay here. The additional delay was varied from 0 ms to 200 ms at intervals of 50 ms. The additional delay of each system (i.e., between the master and slave terminals) was set to 0 ms for simplicity. We repeated the task 10 times for each additional delay.

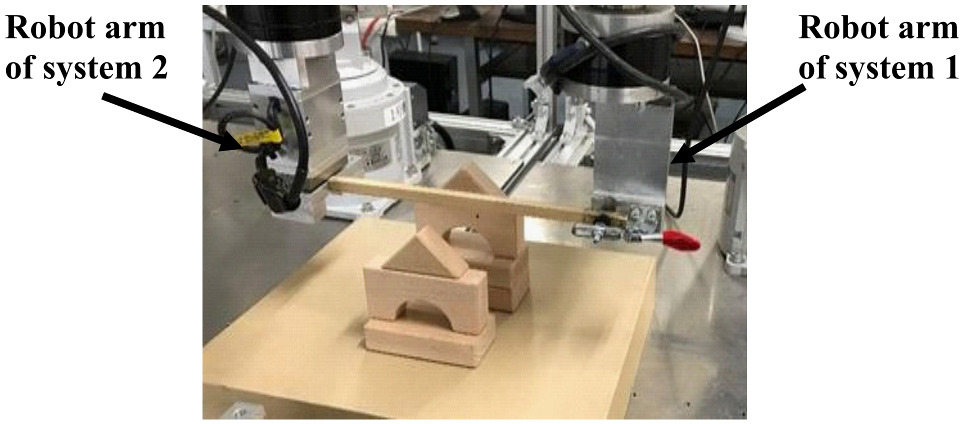


Figure 2.4: Positional relation between wooden stick and blocks.

To assess the influence of network delay, we employ the average work time which is defined as the average time from the moment the task is started until the instance the second building block is dropped. We also use the average force at each robot and the

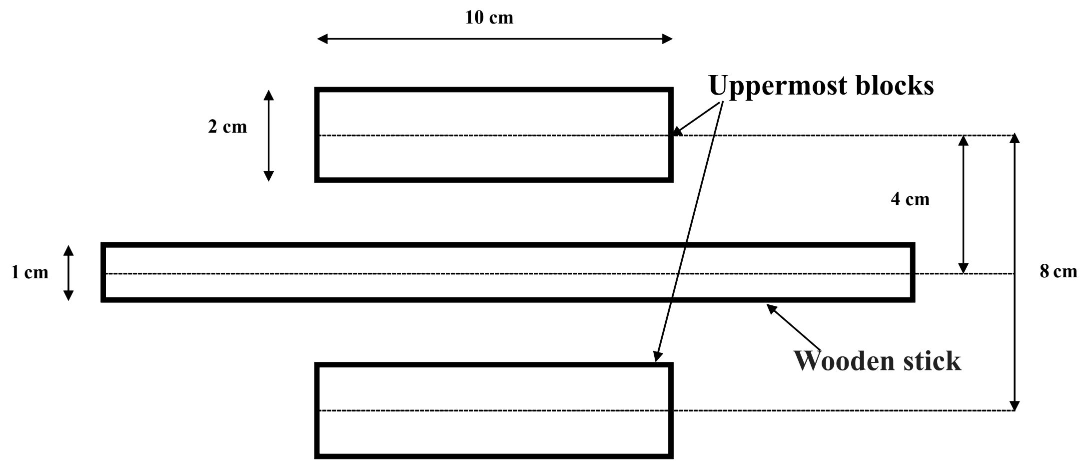


Figure 2.5: Plane view arrangement of stick and blocks.

average reaction force at each haptic interface device.

2.4 Experimental results

We show the average work time as a function of the additional delay in Fig. 2.6. We also plot the average force at the robots of systems 1 and 2, and the average reaction force at the haptic interface devices of systems 1 and 2 in Figs. 2.7 and 2.8, respectively. The 95 % confidence intervals are also illustrated in the figures.

In Fig. 2.6, we notice that as the additional delay becomes larger, the average work time tends to increase. This is because the force of the robots and the reaction force outputted by the haptic interface devices increase; this makes the task more difficult [86].

Figures 2.7 and 2.8 reveal that the average force of the robots of systems 1 and 2, and the average reaction force of the haptic interface devices increase with the additional delay. These increases in average force/average reaction force result in deterioration of operability of the haptic interface device. We can also see in the figures that the average force and average reaction force of system 2 are smaller than those of system 1. This is because the force can be dissipated somewhat due to bending of the wooden stick. We can further confirm that the average reaction force of the haptic interface devices in Fig. 2.8 is one-fifth of the average force of the robots in Fig. 2.7 (note that the force mapping ratio is 1:5 as mentioned in Section 2.3).

In order to investigate behaviors of systems 1 and 2, we plot the position of the robot, force of the robot, and reaction force of the haptic interface device for systems 1 and 2 when we set the additional delay to 50 ms in Figs. 2.9 and 2.10, respectively. In the figures, we show the results only in the front-back direction because the other directions have smaller results than the front-back direction. We can see in Figs. 2.9 and 2.10 that the position, force, and reaction force of system 2 are similar to those of system 1. This is the effect of the master-slave relation.

We also observe in the figures that the average values of the force and reaction force of system 2 are smaller than those of system 1. Furthermore, we see that the directions of the force and reaction force in Figs. 2.9 (b) and 2.10 (b) are opposite to those in Figs. 2.9 (c) and 2.10 (c). This is because the two types of force obey the action-reaction law.

2.5 Summary

In this chapter, we examined the influence of network delay on cooperation between the two remote master-slave robot systems with force feedback by performing cooperative work of carrying a wooden stick together. We saw that the spatial and temporal synchronization between the master and slave robots deteriorates, as the network delay becomes larger. As a result, the average work time, the average force of the robots, and the average reaction force of the haptic interface device increase. Larger forces make the system unstable and difficult to operate. This results in degradation of operability (that is QoE), therefore, we conclude that to eradicate this problem, it is essential to employ QoS control to achieve efficient operation during unfavorable network conditions.

In the next chapter, we study the effects of three types of QoS control for cooperative work to abate the influence of network delay in remote robot systems with feedback using master-slave relation by experimentation. In Chapter 4, we study the influence of network delay and propose QoS control to mitigate the influence of network delay in remote robot systems with force feedback with peer-to-peer relation.

For our future work, we need to study the influence of asymmetric network delay, delay jitter, and packet loss. We should also study several types of cooperative work and employ suitable QoS control to mitigate the influence of different network parameters. It is also important to conduct QoE assessment to compare the several types of QoS control.

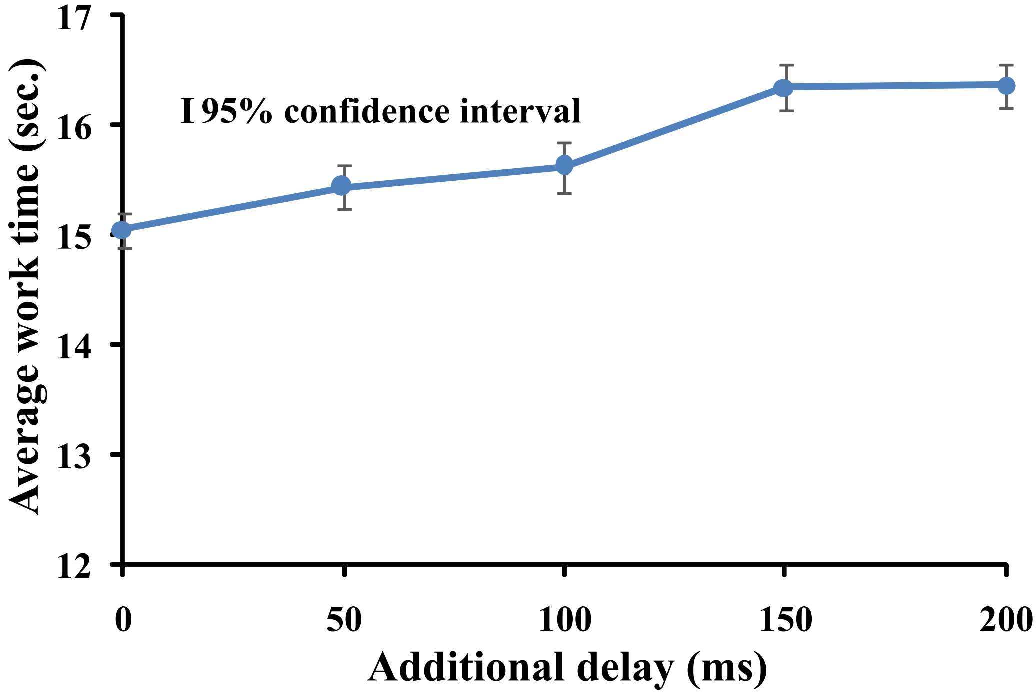


Figure 2.6: Average work time versus additional delay.

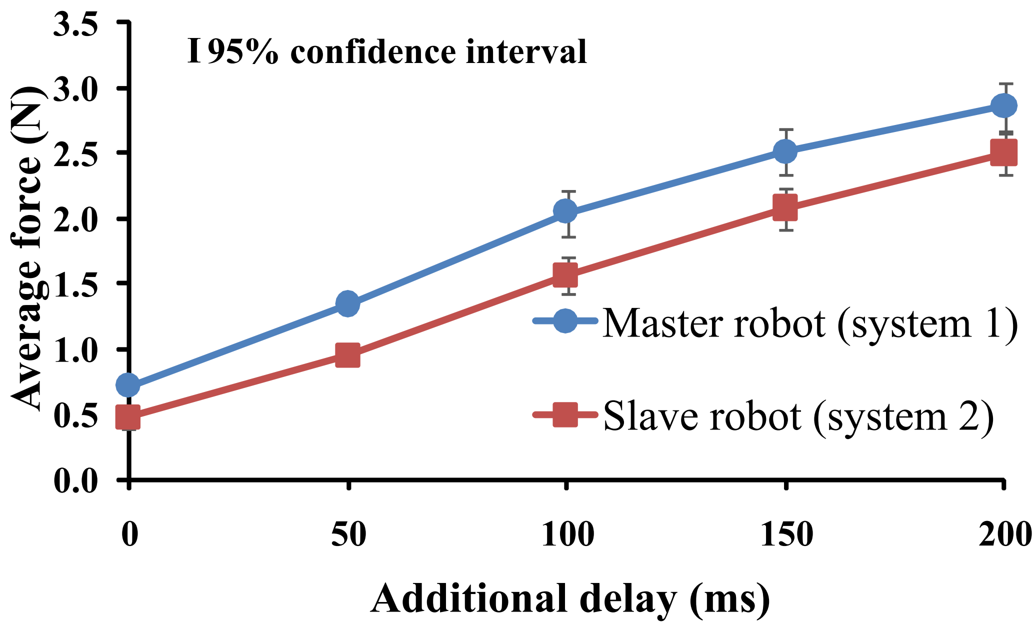


Figure 2.7: Average force at each robot versus additional delay.

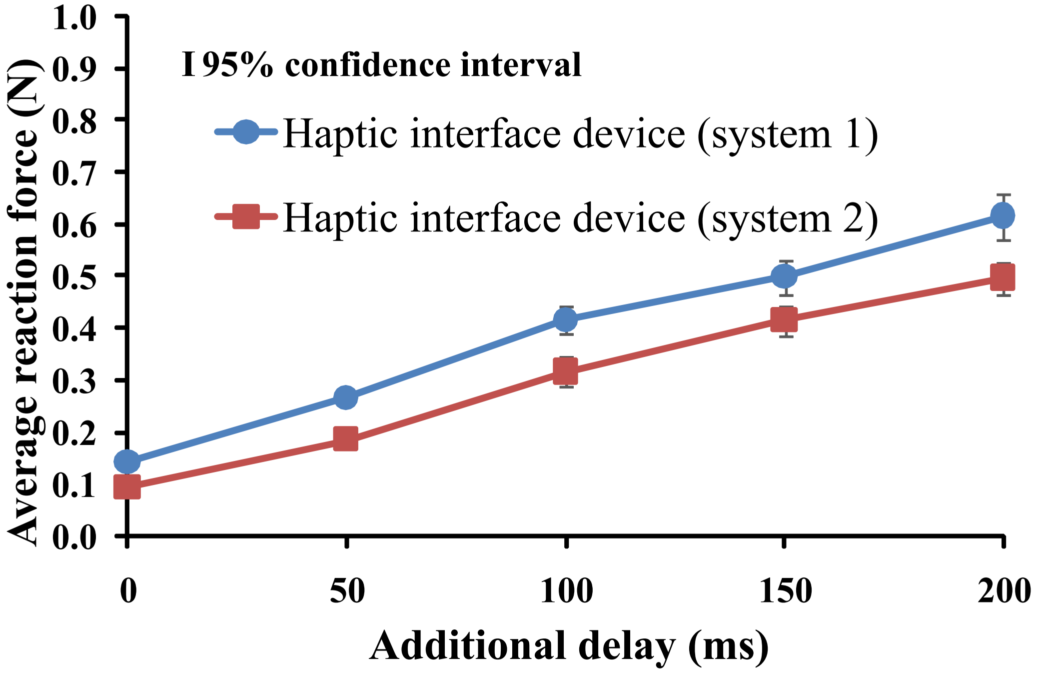
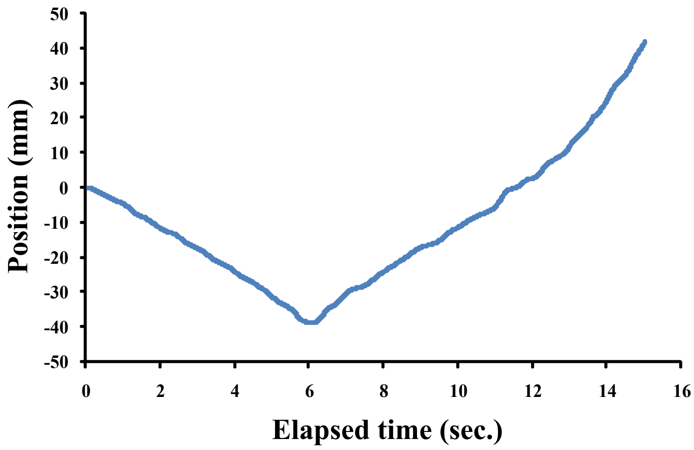
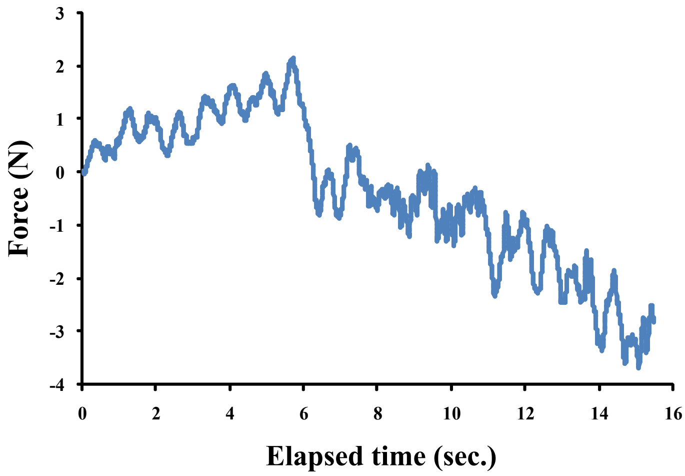


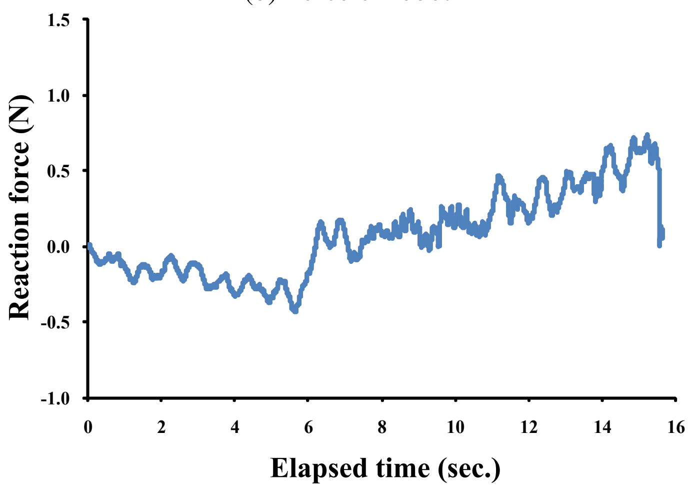
Figure 2.8: Average reaction force at each haptic interface device versus additional delay.



(a) Position of robot

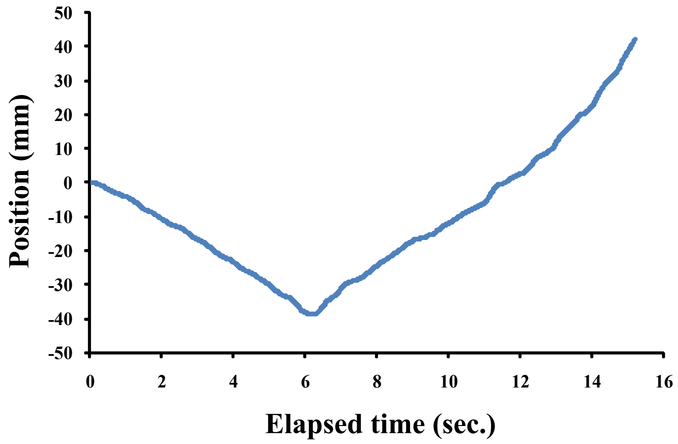


(b) Force of robot

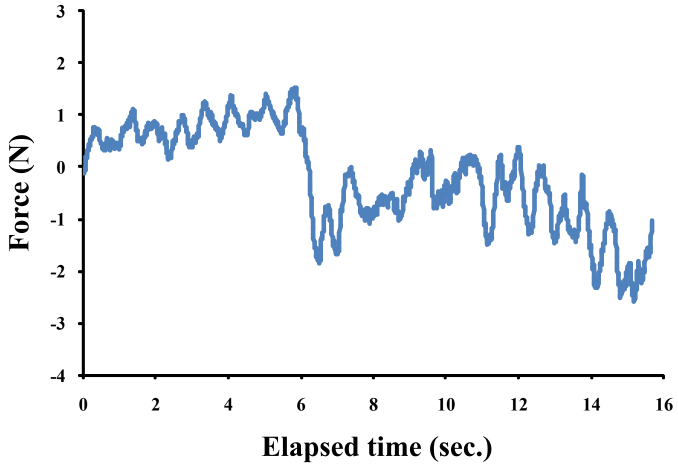


(c) Reaction force of haptic interface device

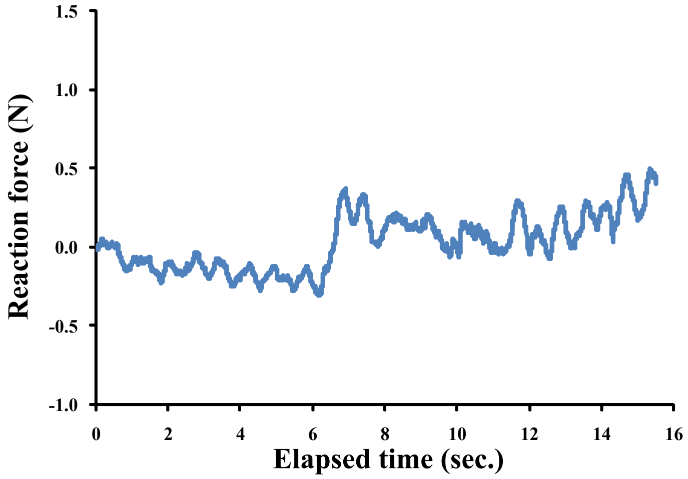
Figure 2.9: Position, force, and reaction force versus elapsed time in system 1.



(a) Position of robot



(b) Force of robot



(c) Reaction force of haptic interface device

Figure 2.10: Position, force, and reaction force versus elapsed time in system 2.

Chapter 3

Effects of QoS control in remote master-slave robot systems with force feedback

3.1 Introduction

In Chapter 2, we clarify the influences of network delay in the remote master-slave robot systems with force feedback for cooperative work. We find out that as the network delay increases, the spatial and temporal synchronization between the master and slave robots deteriorates. This increases the average work time, the average force of the robots, and the average reaction force of the haptic interface device, which may seriously damage the object. Larger force also makes it difficult to perform the given task and degrade operability seriously. To solve these problems, it is essential to use QoS control to mitigate the influence of network delay.

A number of excellent QoS control techniques for the remote robot systems with force feedback has been proposed in the recent years [90]-[94]. In [91], the authors have investigated effects of the adaptive Δ-causality control in the remote master-slave robot systems with force feedback. They show that the influence of network delay between the remote master and slave systems has been significantly mitigated by using the control. On the other hand, the effect of the control for the network delay in each remote robot system has not been clarified quantitatively.

In [92], the robot position control with force information is proposed to weaken large force that is exerted on an object by adjusting the robot position finely in the direction to abate the force in cooperative work for the case of equal relation between robots. In

[93], the robot position control with force information is enhanced by using the relation between the force exerted on the object and its length. However, the effect of the control has not been verified for the remote master-slave robot systems.

In this chapter, we study the effects of the adaptive Δ-causality control and robot position control with force information in the remote master-slave robot systems with force feedback for a cooperative work. In the adaptive Δ-causality control, the output timing of the position of the master robot is varied dynamically to reduce the difference in position between the robots to achieve smooth completion of work. In the robot position control with force information, the position of the robot is changed to reduce the force exerted on the object. We also clarify the effect of a combination of the adaptive Δ-causality control and robot position control with force information to find out the most effective control.

The remainder of the chapter is written as follows. Section 3.2 explains the system configuration. Section 3.3 elaborates the adaptive Δ-causality control and robot position control with force information, and Section 3.4 discusses the experiment method. Section 3.5 illustrates experimental results. The summary of this chapter is presented in Section 3.6.

3.2 Remote master-slave robot systems

The configuration of the remote master-slave robot systems is illustrated in Fig. 3.1. The experimental setup consists of the two remote robot systems (called the master and slave systems here). Each system consists of a master terminal and a slave terminal. The master terminal is composed of PC for haptic interface device and PC for video, which are connected by using switching hub. The former PC has a haptic interface device (3D Systems Touch [61]). A switching hub is used to connect PC for industrial robot and PC for video at the slave terminal. PC for industrial robot is directly connected to an industrial robot via an Ethernet (100BASE-TX) cable. The industrial robot consists of a robot arm (RV-2F-D by Mitsubishi Electric Corp.), a robot controller (CR750-Q), a force interface unit (2F-TZ561). A force sensor (1F-FS001-W200) is attached to the robot arm. The robot arm of each system has a toggle clamp hand (see Fig. 3.2).

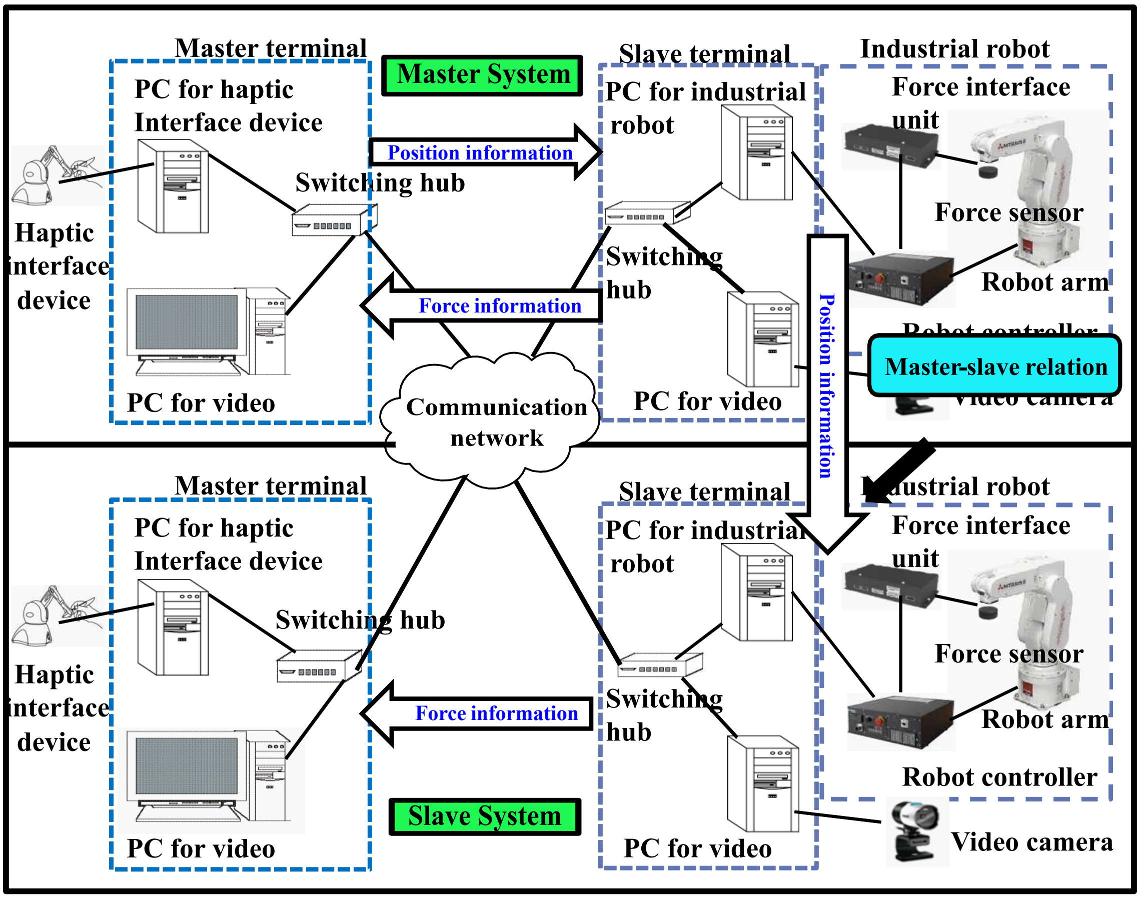


Figure 3.1: Configuration of remote robot systems with force feedback.

3.3 QoS control

We explain the two types of QoS control: The adaptive Δ-causality control and the robot position control with force information in this section.

3.3.1 Adaptive Δ-causality control (ADC)

When there is a large network delay between the master system and slave system, the position information of the robot of the slave system lags behind that of the master system. This difference in position results in large force exerted on an object carried by the robots. In the adaptive Δ-causality control [91], the output timing of the master robot position information is delayed dynamically according to the network delay so that both the master and slave robots move at the same time. The output timing of the position information at the master robot is set to the generation time + Δ. The value of Δ is dynamically adjusted in accordance with the network delay. Let us denote the value of Δ at time t by Δ_t here. We obtain the value of Δ_t by using the smoothed network delay d_t

at time t by the following equation:

$$\Delta_t = \alpha\Delta_{t-1} + (1-\alpha)d_t \tag{3.1}$$

where α is a smoothing coefficient and is set to 0.998 [91].

3.3.2 Robot position control with force information (RPC)

In the robot position control with force information, the robot position is adjusted finely according the force applied to the object carried by the robot arms. In [93], the authors obtain the relation between the force and position information as a function of the length of the stick that is held by the robot arms. The new position information $\hat{\boldsymbol{S}}_t$ is obtained by adding $\boldsymbol{P}$ to position $\boldsymbol{S}_t$ as follows:

$$\hat{\boldsymbol{S}}_t = \boldsymbol{S}_t + \boldsymbol{P} \tag{3.2}$$

The robot arm is moved by $\boldsymbol{P}$ in the direction so as to weaken the large force applied to the stick. In this paper, the robot position control with force information is applied to only the slave system. This is because applying the robot position control with force information in one system yields better results than in the two systems [94].

3.3.3 Combination of ADC and RPC

In this QoS control, a combination of ADC and RPC is applied to the remote master-slave robot systems. The adaptive Δ-causality control (ADC) is applied to System 1 (ie., the master system), and the robot position control with force information is applied to System 2 (ie., the slave system).

3.4 Experiment method

In the experiment, we carried out a task of touching paper blocks with a wooden stick held by the two robot arms. We stacked the wooden building blocks before and behind the wooden stick. We also placed a paper block on each uppermost wooden building block as shown in Fig. 3.2. We performed a task of touching each paper block of the stacked building blocks (front and back) with the wooden stick held by the two robot arms by using the haptic interface device of the master system while watching video. The two paper blocks are placed at 80 mm from each other. The initial position of the wooden stick is set so that it is at an equal distance from both the paper blocks (i.e., 40 mm from each paper block). The paper block on the front side is touched in 5 seconds and that on the back side in 10 seconds (i.e., it took about 15 seconds to complete the task). The force mapping ratio between the haptic interface device and the robot arm in each system is set to 1:2 [88]. The robot arm of each system is allowed to move in front and back direction. The movement in left and right, and up and down directions is restricted for simplicity. In

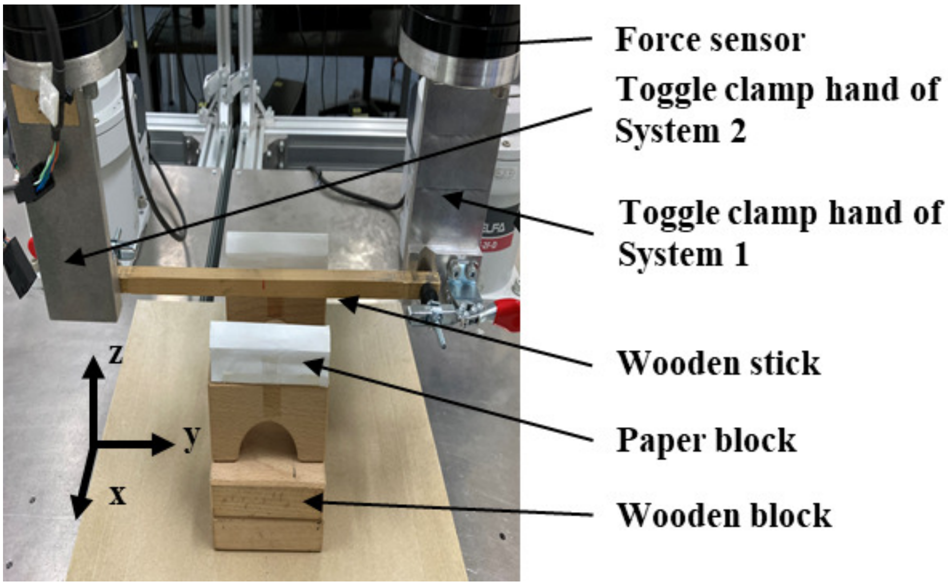


Figure 3.2: Arrangement of paper and wooden blocks.

the remote master-slave robot systems, a network emulator is used to connect the master and slave systems [89], and we add a constant delay to each packet sent between the two robots, and between the master and slave terminals of each system (the one-way constant delay is called the *additional delay* here). The experiment was carried out for different network delays between the two PCs for industrial robots, and between master and slave terminals of master system. The additional delay between the master and slave robots (i.e., the two slave terminals) was varied from 0 ms to 200 ms at intervals of 50 ms. The additional delay of the master system (i.e., between the master and slave terminals) was varied from 0 to 200 at intervals of 100 ms. It should be noted that the additional delay between the master and slave terminals of the slave system was always set to 0 ms in this paper because the additional delay does not affect the task. We repeated the task 10 times for each combination of additional delays.

To compare effects of different types of QoS control, we use the average of average force and the average of maximum force at each robot as performance measures. The average of the average force at each robot is defined as the 10 times average of the temporal average force during each task at each robot. The average of maximum force is obtained by averaging the maximum force during each task at each robot.

3.5 Experimental results

We plot the average of average force and the average of maximum force versus the additional delay between the master and slave robots for additional delays of 0 ms and 200 ms between the master and slave terminals of the master system in Figs. 3.3 and 3.4, respectively. The 95 % confidence intervals are also included in the figures. Furthermore, RPC and ADC stand for the robot position control with force information and the adaptive Δ-causality control, respectively. RPC + ADC means a combination of RPC and ADC. No control does not carry out any QoS control.

In Figs. 3.3 and 3.4, we see that the average of average force and the average of maximum force for additional delays of 0 ms and 200 ms between the master and slave terminals of the master system are almost the same. This means that the average of average force and the average of maximum force hardly depends on the additional delay between the master and slave terminals of the master system.

We also see in the figures that the average of average force and the average of maximum force for RPC + ADC are the smallest. ADC has the second smallest, RPC has the third smallest, and no control has the largest. Therefore, ADC has larger effect than RPC.

We further observe in the figures that the slave system tends to have larger average of average force and average of maximum force than the master system. We are now clarifying the reasons; one of the reasons may be the difference in direction of the toggle clamp hand setup between the two robots.

To examine the effects of different types of QoS control more clearly, we show the force versus the elapsed time of the master and slave robots from the beginning of each task in Fig. 3.5, where the additional delay between the master and slave robots that between master and slave terminals of the master system is 200 ms. Figures 3.5 (a) through (d) plot the results for no control, RPC, ADC, and RPC + ADC, respectively. The results for the other combinations of additional delays are not shown here because the results are almost the same as those in Fig. 3.5.

In Figs. 3.5 (a) and (b), we observe that the force fluctuations are much significant for no control, while the fluctuations are reduced when RPC is used. We also notice that the force jumps up and the sign of the force is also reversed at about 6 seconds. The reason is that the direction of movement to touch the paper block on the back side after touching the paper block on the front side is changed at about 5 second as mentioned in Section

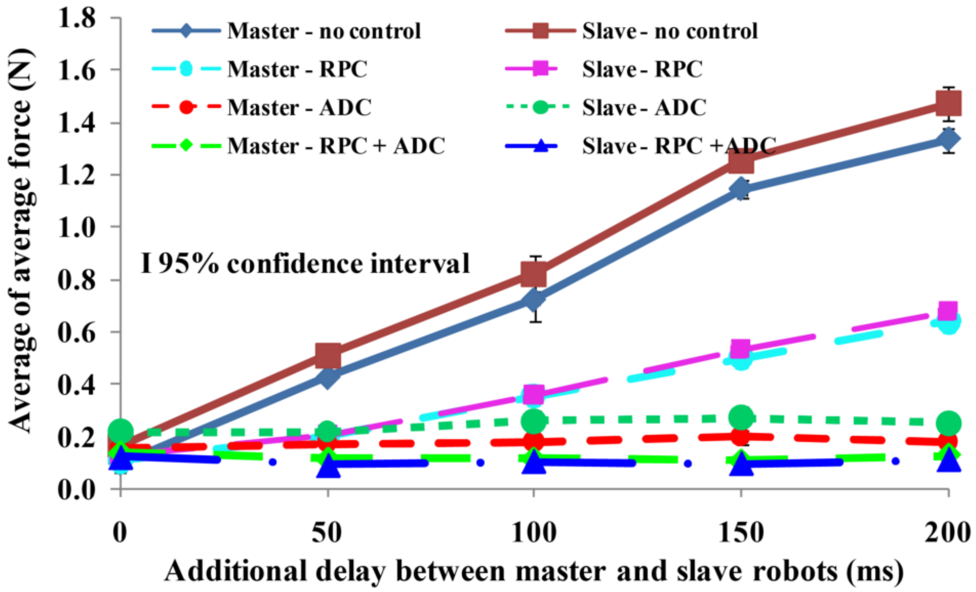
3.4. On the other hand, we can see that the force of the robots hardly increases with the additional delay in Figs. 3.5 (c) and (d). We note that force of the robots for RPC + ADC is smaller than that of ADC.

Based on the aforementioned considerations, we can say that the combination of the robot position control with force information and the adaptive Δ-causality control is the most effective.

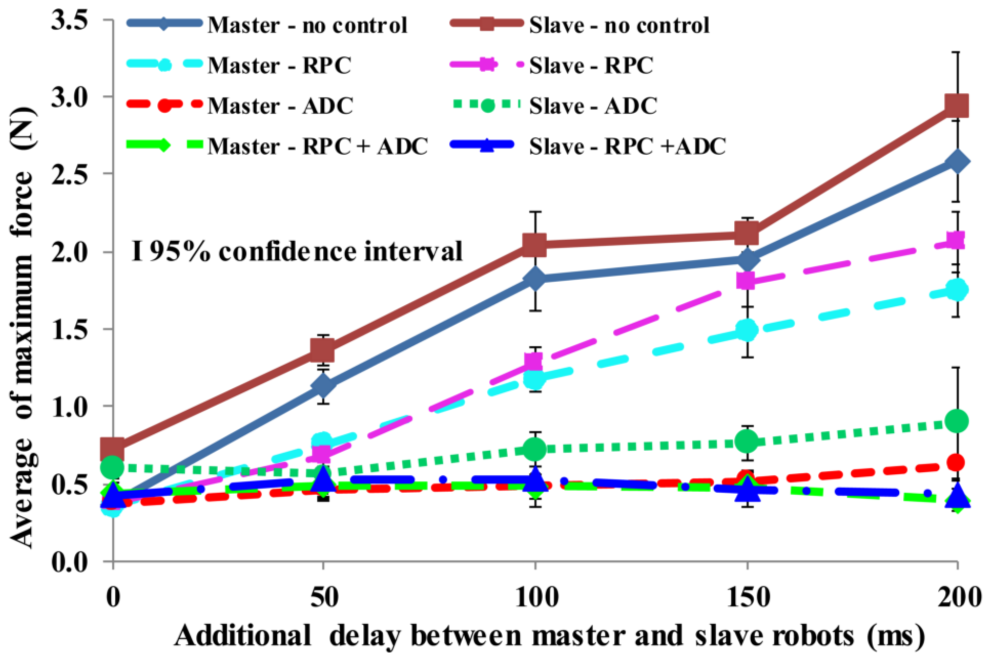
3.6 Summary

In this chapter, we compared the following three types of QoS control: The adaptive Δ-causality control, the robot position control with force information, and a combination of both. As a result, we illustrate that the combination of the adaptive Δ-causality control and the robot position control with force information is the most effective. We also confirmed that force fluctuations are alleviated greatly when compared to the other two types of QoS control. Furthermore, the effect of the adaptive Δ-causality control is larger than that of the robot position control with force information.

As the next step in this research, we will employ the combination of the adaptive Δ-causality control and the robot position control with force information to other types of cooperative work.

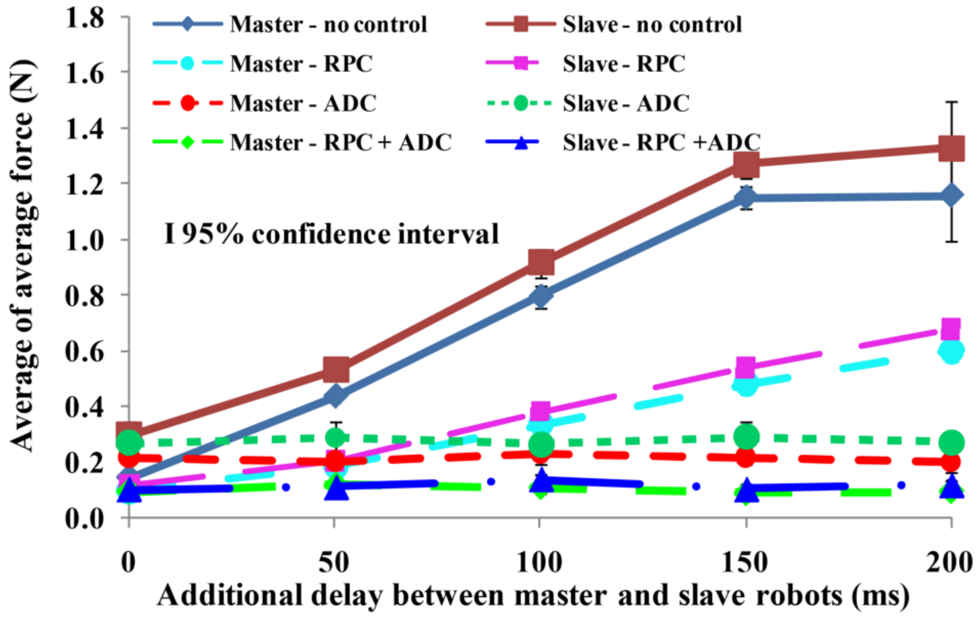


(a) Average of average force

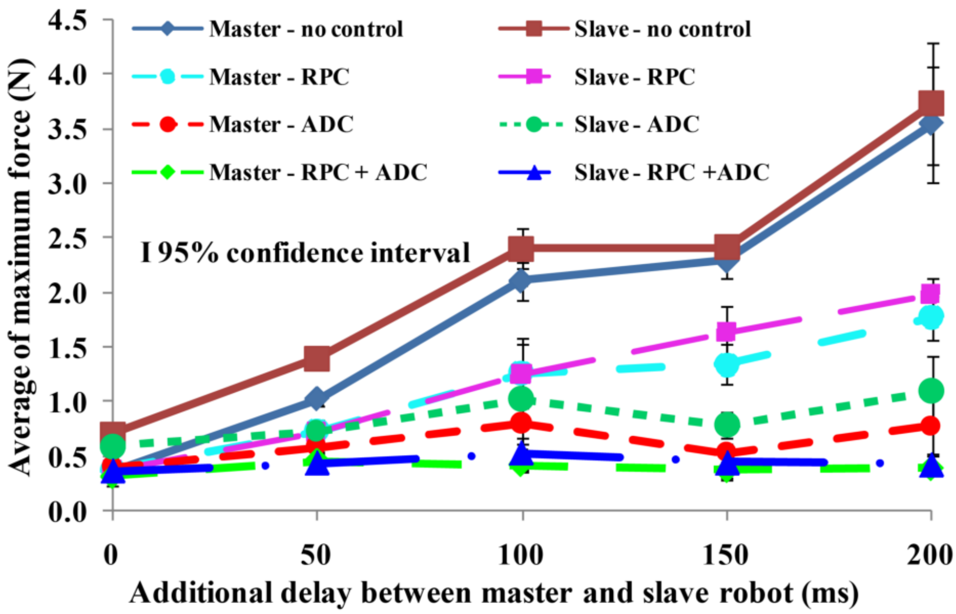


(b) Average of maximum force

Figure 3.3: Average of average force and average of maximum force for additional delay of 0 ms in master system.

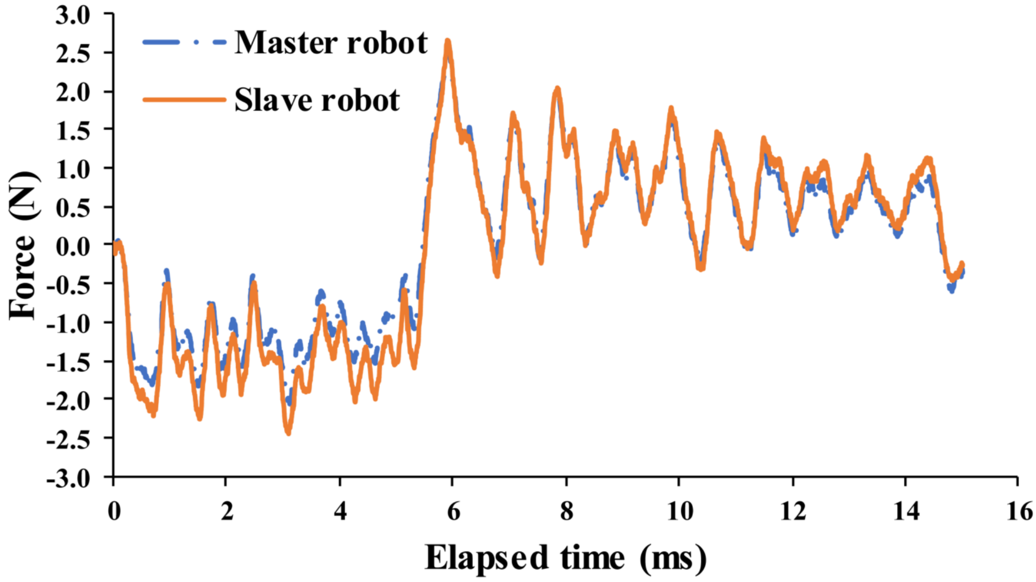


(a) Average of average force

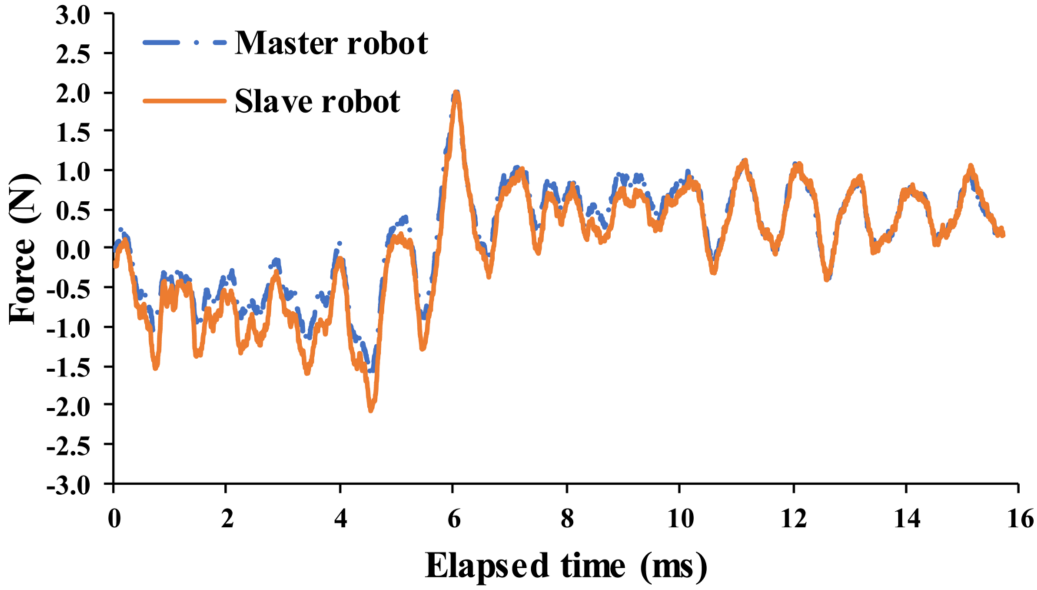


(b) Average of maximum force

Figure 3.4: Average of average force and average of maximum force for additional delay of 200 ms in master system.

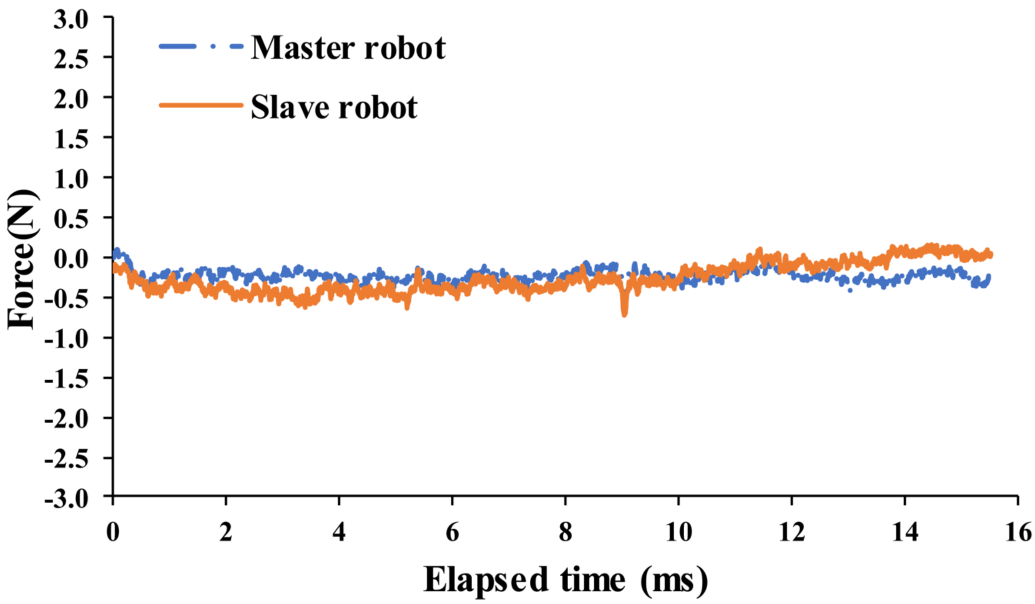


(a) No control

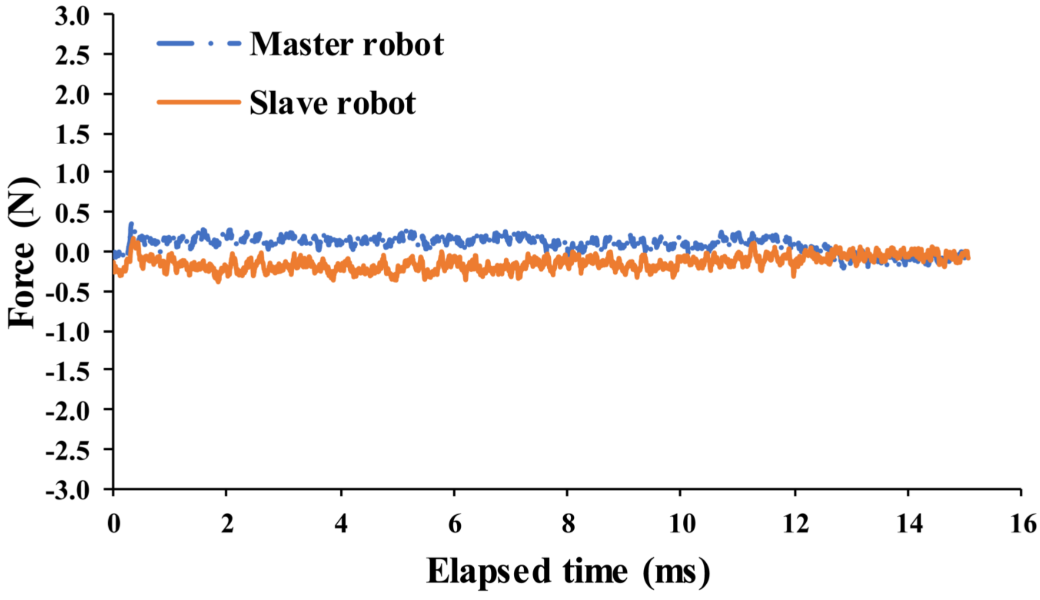


(b) RPC

Figure 3.5: Force versus elapsed time (additional delay: 200 ms).



(c) ADC



(d) RPC + ADC

Figure 3.5: Force versus elapsed time (additional delay: 200 ms).

Chapter 4

Effects of adaptive Δ-causality control in remote robot systems with force feedback

4.1 Introduction

With multiple remote robot systems, there are many ways to achieve cooperation among the remote robot systems. We consider two types of relationships between the systems; namely the master-slave relation and peer-to-peer relation to clarify how network delay affects each relationship. In the master-slave relation, one system acts as the master, and the other system acts as the slave. In the peer-to-peer relation, the two systems act as independent systems working together to complete a given task. In Chapters 2 and 3, we have discussed about the influence of network delay and effects of various types of QoS control [90]-[98] for remote master-slave robot systems with force feedback. In this chapter, we deal with remote robot systems with peer-to-peer relation.

In [88], the authors study the influence of network delay in cooperative work of carrying an object between two remote robot systems with force feedback and find that the force exerted on the object increases as the network delay becomes larger. They also show that larger force is applied while changing the direction of the movement during the cooperative work. If the object is fragile, the large force may break the object. Therefore, we need to avoid large force.

In another study [96], the authors apply the adaptive Δ-causality control [97], which dynamically varies the output timing of position information in accordance with the network delay, to the two robots to weaken the force exerted on the object. They illustrate the effectiveness of the control by experiment. However, influences of network delay between the robots, and network delay between the haptic interface device and robot have not been clarified. Also, the work is conducted by a single user; that is, the user manipulates two haptic interface devices to move the remote robots by both hands. Since the devices can be manipulated by two users, we need to clarify the effect of the adaptive Δ-causality control for the cooperative work by two users. Furthermore, the control can be employed to the robot and haptic interface device of each system. However, the effect of the control in this case has not been investigated so far.

In this chapter, we propose the local and global adaptive Δ-causality control to mitigate influences of network delay in remote robot systems with force feedback using peer-to-peer relation for a cooperative work. In the local adaptive Δ-causality control, the adaptive Δ-causality control is carried out between two robots, or between a haptic interface device and a robot in each system. In the global adaptive Δ-causality control, the adaptive Δ-causality control is applied to both between the robots, and between the haptic interface device and robot of each system. We also compare effects of the local adaptive Δ-causality control between robots, local adaptive Δ-causality control between device and robot, and global adaptive Δ-causality control to find the best control among the three by experiment. The experiment is done by two different users instead of a single user handling both the robot systems. We have used the stabilization control with filters [98] to solve instability problems in the system.

The organization of this chapter is as follows. The system configuration and remote operation of the remote robot systems with force feedback are explained in Section 4.2. Section 4.3 proposes the local and global adaptive Δ-causality control, and Section 4.4 elaborates the experiment method. Section 4.5 discusses experimental results. The summary of the chapter is presented in Section 4.6.

4.2 Remote robot systems with force feedback

4.2.1 System configuration

The configuration of two remote robot systems (called *System 1* and *System 2* here) with force feedback is shown in Fig. 4.1. Each system comprises of a master terminal and a slave terminal. The master terminal consists of PC for haptic interface device and PC for video. A haptic interface device (3D Systems Touch [61]) is connected to the master terminal. A switching hub is used to connect the two PCs. The slave terminal consists

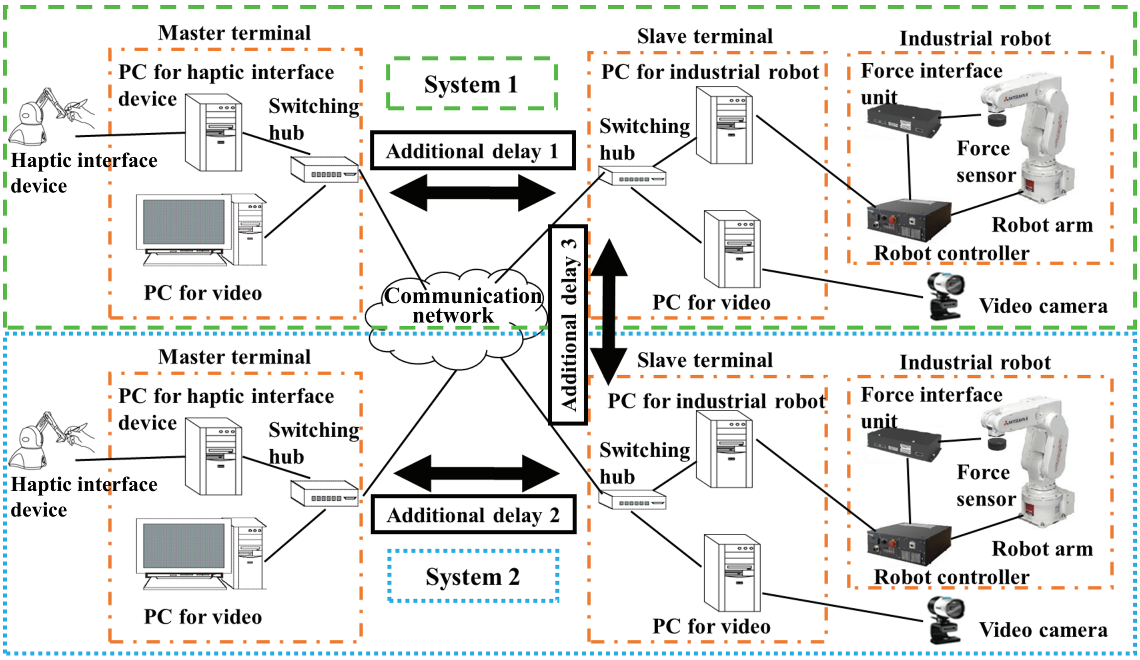


Figure 4.1: Configuration of remote robot systems with force feedback.

of PC for industrial robot and PC for video. The two PCs are connected to each other by using a switching hub. An industrial robot is connected to the slave terminal via an Ethernet (100BASE-TX) cable. The industrial robot comprises of a robot arm (RV-2F-D by Mitsubishi Electric Corp. [70]), a robot controller (CR750-Q), and a force interface unit (2F-TZ561). The robot arm is fitted with a force sensor (1F-FS001-W200) to measure the force applied to an object carried by the robot arm. The robot arm has a toggle clamp hand to grasp the object (see Fig. 4.2). A video camera (1920 $\times$ 1080 pixels) is connected to the slave terminal.

4.2.2 Remote operation

In each system, the robot arm at the slave terminal can be remotely operated by a user at the master terminal by using the haptic interface device while perceiving the reaction force. The initial position (i.e., the origin) of the stylus of the haptic interface device corresponds to the initial position (the origin) of the robot arm. The master terminal of each system obtains the position information from the haptic interface device every millisecond [61]. The slave terminal transmits the position information by UDP (User Datagram Protocol) [100] as the transport protocol. The slave terminal employs the real-time control function [70] to acquire the information about the position of the robot arm. The real-time monitor function [70] is used by the slave terminal to get the force sensor information from the robot controller every 3.5 milliseconds [86]. The two types of information are transmitted from the robot controller to the slave terminal by UDP. The slave terminal sends the information to the master terminal in each system.

The slave terminal of each system sends the position information of the robot arm to that of the other system, to judge the direction of movement of the robot arms during the cooperative work. Each slave terminal judges in this paper that the movement direction is changed when each robot arm has continuously moved in the opposite direction 50 [96] or more times.

In our experiment, two different users manipulate the haptic interface devices of System 1 and System 2 while watching videos.

4.3 QoS control

In the adaptive Δ-causality control [96], the output timing of the position information is dynamically delayed in accordance with the network delay. The output timing of the position information is set to the generation time (i.e., timestamp) + Δ (>0) seconds, and the value of Δ is changed dynamically according to the network delay. The time when the position information is generated at a source (i.e., each master or slave terminal in this paper) is attached as the timestamp along with the position information that is transmitted to destinations (each master or slave terminal). We here assume that the global clock [96] is used; that is, the clock ticks have the same value and speed among the systems. Each terminal should send the current value of Δ to the other terminal at regular intervals as well as when the value is changed owing to network delay jitter [96] (we do not handle the delay jitter for simplicity as mentioned in Section 4; note that we can absorb the delay jitter to some extent by setting the value of Δ as the network delay plus the buffering time for the jitter [97]). The largest value is selected by the terminal as Δ from among the latest-received values (including its own value) for simplicity in this paper [96]. All the terminals use the same method to determine the value of Δ. Let us denote the value of Δ at time t ($t \geq 1$) by Δ_t here. We obtain the value of Δ_t is by using the smoothed network delay d_t measured at time t as follows:

$$\Delta_1 = d_1 \tag{4.1}$$

$$\Delta_t = \alpha\Delta_{t-1} + (1-\alpha)d_t \qquad (t \geq 2) \tag{4.2}$$

where α is a smoothing coefficient and is set to 0.998 [91].

In this study, two kinds of the adaptive Δ-causality control are handled. One is the local adaptive Δ-causality control (called *LADC* here), and the other is the global adaptive Δ-causality control (called *GADC*). In LADC, we have two cases: Control between the two robots (*LADC-RR*), and control between the haptic interface device and robot in each system (*LADC-DR*). In GADC, both LADC-RR and LADC-DR are carried out in the systems.

4.3.1 Local adaptive Δ-causality control (LADC)

4.3.1.1 LADC-RR

When the network delay between the two robots increases, the difference in position between the two robots becomes larger. This difference in position results in large force applied to an object carried by the robots especially when the direction of movement is changed. In LADC-RR, the output timing of the robot position information is adjusted dynamically in accordance with the network delay between the robots so that both the robots move at the same time. In this paper, for simplicity, the network delay from the industrial robot of System 1 (referred to as *robot* 1) to the industrial robot of System 2 (*robot* 2) is set to the same as that from robot 2 to robot 1.

4.3.1.2 LADC-DR

In this case, the adaptive Δ-causality control is applied to reduce the influence of difference in network delay between the haptic interface device and robot of each system between the two systems. The value of Δ in each system are set so that each robot is moved at the same time as the other robot. For instance, when the delay between the haptic interface device and robot in System 1 is 0 ms and the delay in System 2 is 100 ms, the value of Δ is set to 100 ms in this case so as to decrease position difference between the two robots.

4.3.2 Global adaptive Δ-causality control (GADC)

GADC is a combination of LADC-RR and LADC-DR. In GADC, the output timing of each robot is adjusted for both network delays between the robots and the difference in network delay between the two systems rather than only one of them as in the cases of LADC-RR and LADC-DR. For instance, let us set the network delay between the haptic interface device and robot in System 1 to 0 ms, the network delay in System 2 to 100 ms, and the network delay between the robots to 100 ms. In GADC, the values of Δ at the master terminal and the slave terminal of each system are set to 100 ms because the largest value of network delays is selected as Δ as described earlier. Note that in LADC-RR, Δ at the slave terminal of each system is set to 100 ms; in LADC-DR, Δ of the master terminal of each system is set to 100 ms.

4.4 Experiment method

In this study, we carried out cooperative work of carrying a wooden stick as the object grasped by the two robot arms [96]. In this study, two different users manipulated the two haptic interface devices with their dominant hands while perceiving the force and watching videos.

The wooden building blocks were piled-up before and behind the wooden stick. On each uppermost building block, we placed a paper block as shown in Fig. 3.2. The building blocks are arranged so that the two paper blocks are at the same height. The task was to touch each paper block (front and back) by the wooden stick. The two paper blocks were placed at 80 mm from each other. The initial position of the wooden stick was set so that it is at an equal distance from both the paper blocks (i.e., 40 mm from each paper block). The paper block on the front side is touched in about 5 seconds and that on the back side in around 10 seconds (i.e., it took about 15 seconds to complete the task). This method is used to move the wooden stick in the same way so that we can maintain almost the same movement throughout the experimentation. The two users started each task at almost the same time by hearing a voice cue.

The force mapping ratio between the haptic interface device and the robot arm in each system was set to 1:3 [99]. The robot arm of each system was allowed to move only in front and back direction (i.e., the x-axis) (see Fig. 3.2); the movement in left and right (the y-axis), and up and down (the z-axis) directions was restricted for simplicity.

The two remote robot systems (i.e., Systems 1 and 2) are connected through a network emulator (NIST Net [89]) instead of the communication network in Fig. 4.1 to add a constant delay to each packet sent between the two robots, and between the master terminal and the slave terminal of each system (the one-way constant delay is called the *additional delay* here); the constant delays in both directions are assumed to be same. The additional delay in System 1 (i.e., that between the master terminal and the slave terminal of System 1), that in System 2, and that between the two robots are represented as *additional delay 1*, *additional delay 2*, and *additional delay 3*, respectively (see Fig. 4.1). We do not produce any packet loss by the network emulator, for simplicity. LADC-RR is used to alleviate the influences of additional delay 3, LADC-DR to alleviate the influences of additional delays 1 and 2, and GADC for all the three additional delays. The combination of the delays is expressed as (additional delay 1, additional delay 2, additional delay 3) . The experiment was carried out for different additional delays between the two slave terminals, and between the master terminal and the slave terminal of each system. Additional delays 1 and 2 were changed from 0 ms to 200 ms at intervals of 100 ms. We varied the additional delay 3 between 0 ms and 100 ms. The work was repeated 10 times for each combination of additional delays.

To clarify effects of LADC-RR, LADC-DR, and GADC, we also handle the case where the adaptive Δ-causality control is not carried out (called *No control* here). We use the average of average absolute force and the average of maximum absolute force at each robot as performance measures. The average of the average absolute force at each robot is defined as the 10 times average of the temporal average absolute force at the robot. The average of maximum absolute force is obtained by averaging the maximum absolute force for all the tasks at the robot.

4.5 Experimental results

Fig. 4.2 shows the average of average absolute force and the average of maximum absolute force for No control and LADC-RR, and Fig. 4.3 plots those for No control and LADC-DR. Also, Fig. 4.4 shows those for LADC-RR, LADC-DR, and GADC. We also show the 95% confidence intervals of averages in the figures.

We see from Fig. 4.2 that the average of average absolute force and the average of the maximum absolute force of LADC-RR are smaller than those of No control. We also observe that the differences between LADC-RR and No control when additional delay 3 is 100 ms are larger than those when additional delay 3 is 0 ms. This is the effect of LADC-RR.

On the other hand, from Fig. 4.3, we can see that the differences between No control and LADC-DR are not so large, compared with those between No control and LADC-RR (Fig. 4.2). Therefore, we can infer that LADC-RR has a larger effect than LADC-DR.

From Fig. 4.4, we observe that the average of average absolute force and the average of maximum absolute force are the smallest for GADC. Thus, we can say that GADC is more effective than LADC-RR and LADC-DR. It should be noted that GADC may damage the interactivity, but GADC is better than LADC for the network delays considered in this paper. Fig. 4.4 also reveals that the differences between GADC and LADC-RR are not large. Thus, we carried out t-test to examine whether the differences are significant. As a result of t-test, we found that there exist significant differences between GADC and LADC-RR. The t-test result between averages of average absolute force for robot 1 was as follows: [$t(9) = 4.26$, $p = 0.0013$, one-sided test]; for the other combinations, the t values were larger than 4.26 and the p values were less than 0.0013; this means that GADC is more effective than LADC-RR.

From Figs. 4.2, 4.3, and 4.4, we notice that the average of average absolute force and average of maximum absolute force of robot 1 tend to be smaller than those of robot 2. This is because the two systems are operated by two different users; we confirmed that the difference reversed, when the users switched the robots. We also found that the direction of force of robot 1 is opposite to that of robot 2 (this will be seen later).

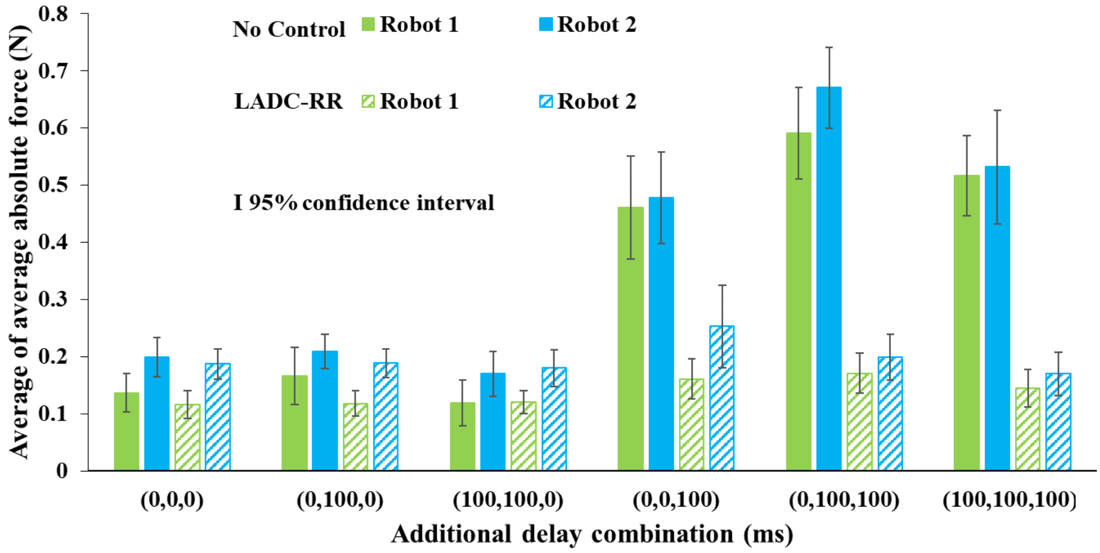
To examine the differences among LADC-RR, LDAC-DR, and GDAC in Fig. 4.4 in further detail, the force versus the elapsed time from the starting of task for LADC-RR, LADC-DR, and GADC for delay combination (0, 100, 100) ms is plotted in Fig. 4.5. The results are typical examples of force versus the elapsed time for LADC-RR, LADC-DR, and GADC in our experiment. From Fig. 4.5, we can clearly see that the force is large for LADC-DR. The force fluctuation is also large especially during the change in the movement direction at about 6 seconds. On the other hand, the force for LADC-RR and GADC hardly increases, and the force exerted during the direction change is much smaller than that of LADC-DR. By comparing Figs. 4.5 (a) and (c), we see that GADC has smaller force than LADC-RR.

In addition, we conducted the experiment for other delay combinations such as (0, 200, 100) ms and (100, 200, 100) ms, and we obtained almost the same results as those in this paper. From these considerations, we can conclude that GADC is more effective than LADC.

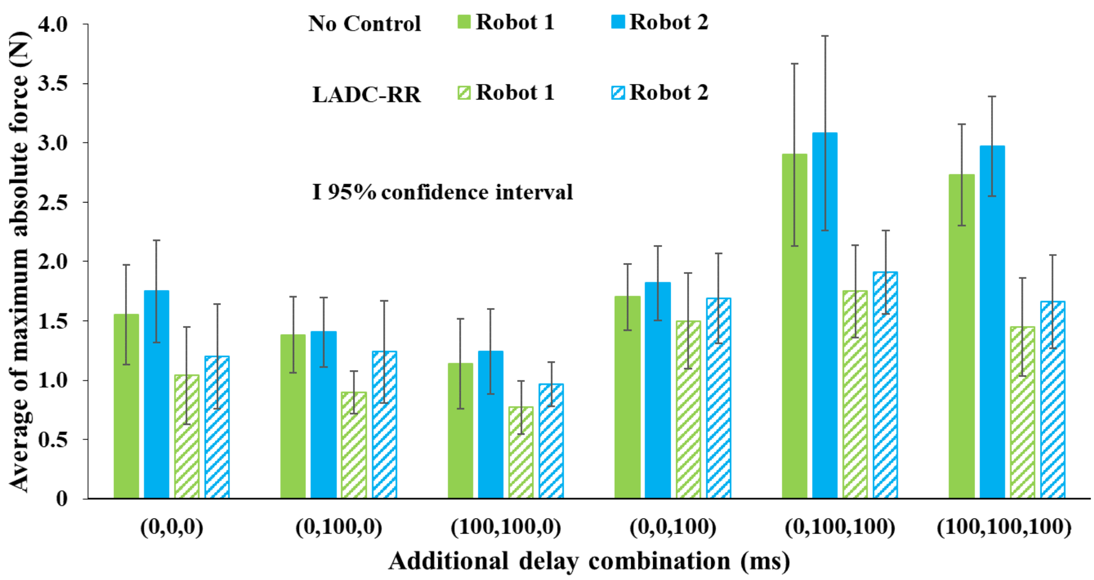
4.6 Summary

In this chapter, we examined the effects of the global and local adaptive Δ-causality control on cooperative work between the two remote robot systems with force feedback with peer-to-peer relation. As a result, we found that the global adaptive Δ-causality control is more effective than the local adaptive Δ-causality control by experimentation. We also confirmed that there exist significant differences between results for the local adaptive Δ-causality control between robots and the global adaptive Δ-causality control.

As the next step of our research, we will focus on collaboration between two users (i.e., the local adaptive Δ-causality control between the two haptic interface devices) to achieve the most effective QoS control. We will also examine effects of the global and local adaptive Δ-causality control for a variety of network environments and system parameters. We also plan to reduce the force fluctuation during the direction change and to apply the global adaptive Δ-causality control to different types of cooperative work.

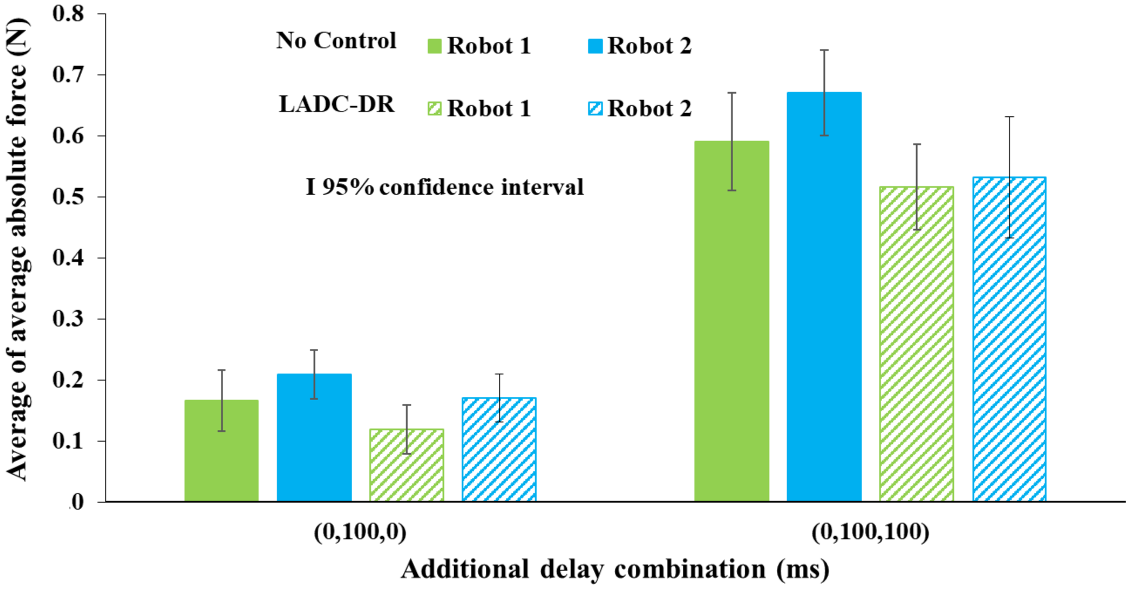


(a) Average of average absolute force

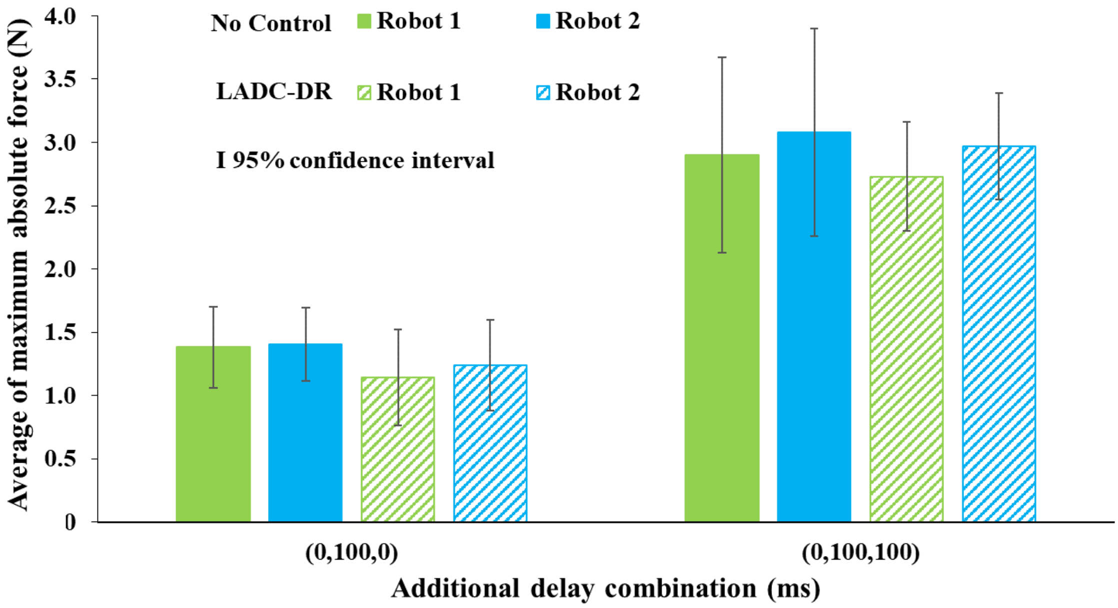


(b) Average of maximum absolute force

Figure 4.2: Comparison between No control and LADC-RR.

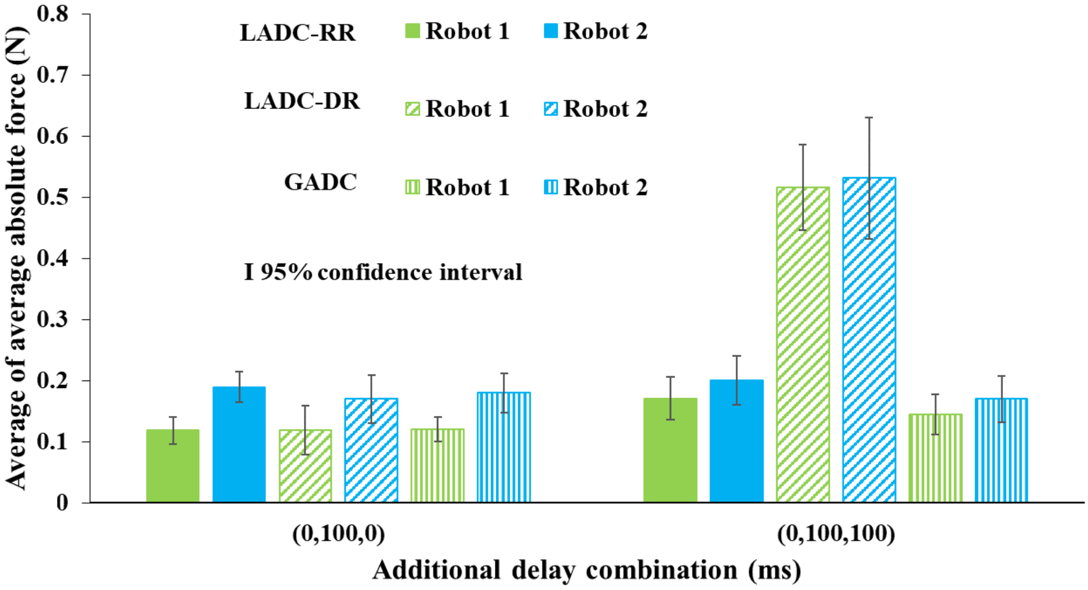


(a) Average of average absolute force

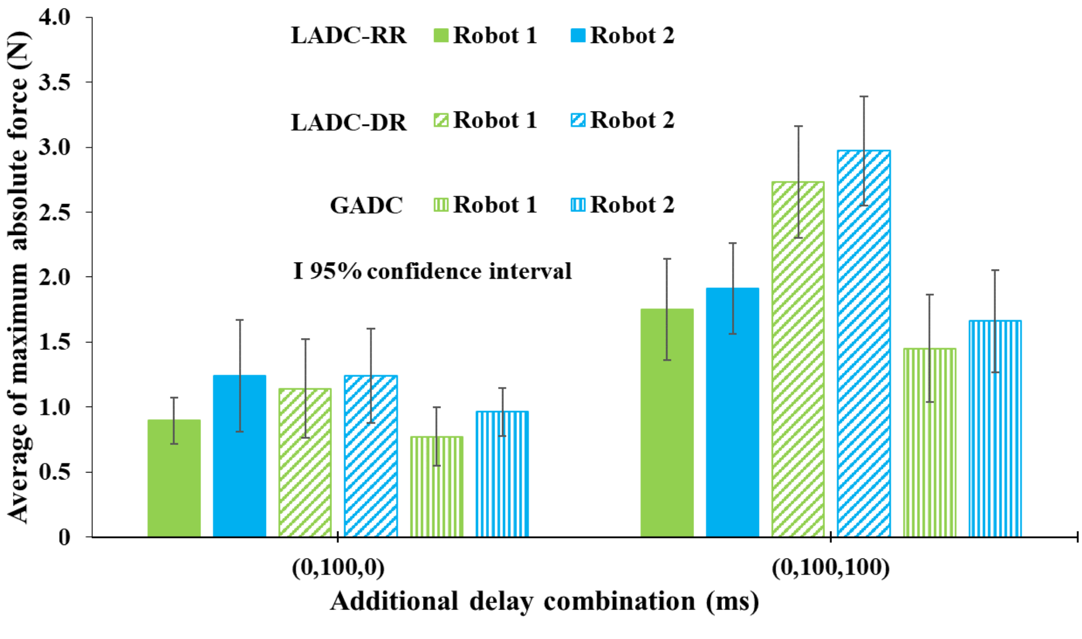


(b) Average of maximum absolute force

Figure 4.3: Comparison between No control and LADC-DR.

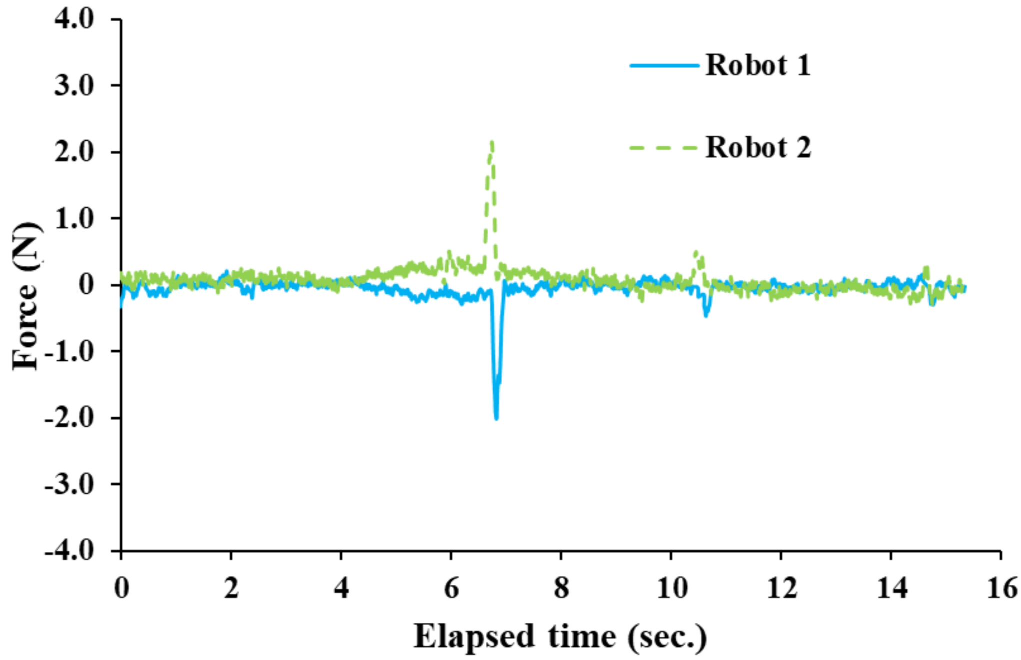


(a) Average of average absolute force

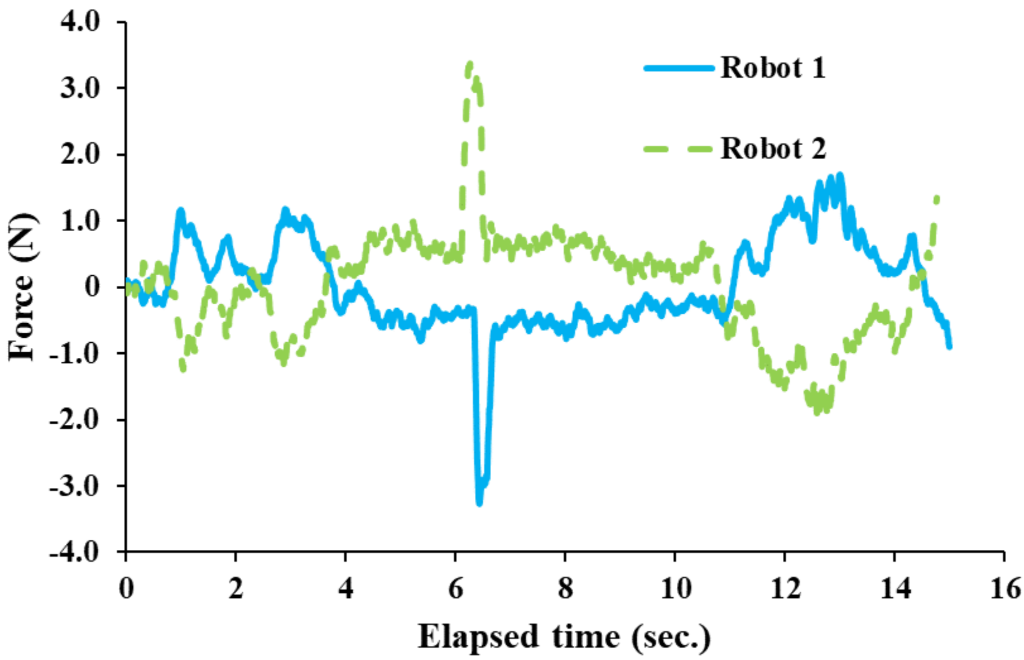


(b) Average of maximum absolute force

Figure 4.4: Comparison between LADC-RR, LADC-DR, and GADC.

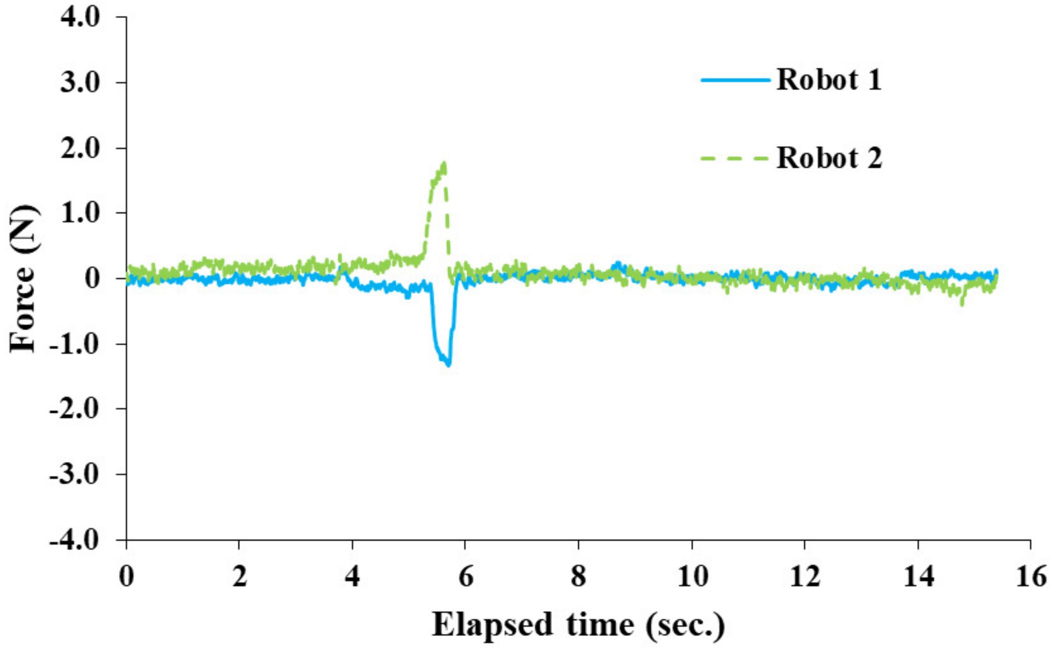


(a) LADC-RR



(b) LADC-DR

Figure 4.5: Force versus elapsed time for delay combination (0,100,100) ms.



(c) GADC

Figure 4.5: Force versus elapsed time for delay combination (0,100,100) ms.

Chapter 5

Conclusion

In this thesis, we studied the influence of network delay and clarified the effects of several types of QoS control to mitigate the influence of the network delay in remote robot systems with force feedback for cooperative work of carrying an object together. We considered two types of relationship between the systems; master–slave relation and peer-to-peer relation. For the master-slave relation, we examined the influence of network delay on the work time, force at the robots and the reaction force at the haptic interface devices by experimentation. Then, we clarified the effects of three types of QoS control; the adaptive Δ-causality control, the robot position control with force information, and a combination of both. We illustrated that the combination of the adaptive Δ-causality control and robot position control with force information should be employed to ensure smooth operation under unfavorable network conditions. For the peer-to-peer relation, we proposed the global and local adaptive Δ-causality control to mitigate the influences of network delay between the robots and in each system. We also clarify that the adaptive Δ-causality control should be employed globally to keep the operability high while performing a cooperative task.

In Chapter 2, we examined the influence of network delay in the remote master-slave robot systems with force feedback for a cooperative task of carrying a wooden stick together by experimentation. Consequently, we found that

- As the network delay becomes larger, the average work time, the average force at robots, and the average reaction force at the haptic interface devices increase.
- It is necessary to perform QoS control to mitigate the influence of network delay and keep the operability high.

In Chapter 3, we clarified the effects of the adaptive Δ-causality control and robot position control with force information to reduce the influence of network delay in the remote master-slave robot systems with force feedback. We also compared the adaptive Δ-causality control, the robot position control with force information, and a combination of both. From experimental results, we found that

- A combination of the adaptive Δ-causality control and robot position control with force information should be employed to alleviate the influence of network delay between robots and in each system.
- The force fluctuations are mitigated greatly while using a combination than using the controls individually
- The effect of the adaptive Δ-causality control is larger than the effect of the robot position control with force information.

In Chapter 4, we proposed and investigated the effects of the local and global adaptive Δ-causality control on cooperative work between the remote robot systems with force feedback for peer-to-peer relation. From experimental results we found that

- The global adaptive Δ-causality control is more effective than the local adaptive Δ-causality control by experimentation.
- There exist significant differences between results for the local adaptive Δ-causality control between robots and the global adaptive Δ-causality control.

As our future work, we will focus on using the combination of the adaptive Δ-causality control and robot position control with force information to other types of co-operative work between robots such as handing over objects. We also plan to investigate influence of network delay on collaboration between two users and to clarify the effects of adaptive Δ-causality control to achieve high operability. Although we have studied the influence of network delay in this thesis, it is essential to examine the influences of other network parameters such as packet loss and delay jitter on collaboration between robots. These kinds of investigations are crucial not only for collaboration between robots for performing a cooperative work, but also for other types of collaboration such as cooperation between human and robots. We should also study the effects of the global adaptive Δ-causality control for hybrid systems in which various types of cooperative work is performed together. For example, the cooperative work in which two robots carrying an object and handing it over to a mobile robot, which deliver the object to a human for real-time safety-critical applications such as disaster rescue.

The results presented in this thesis can be useful for researchers and scientists in academics and industries alike. The QoS control discussed in this thesis can be enhanced for developing a system with high interactivity and operability. Researchers can also use the proposed QoS control in this thesis to various types of cooperative work and compare their results as the effects of the control may differ for different cooperative works. With current pandemic situation, the applications that use remote robot control has increased exponentially. For example with the need for social distancing and minimal human interaction, remote robot systems with the adaptive Δ-causality control can be used in service industries to achieve high operability. The proposed methods can also be used in real-time safety-critical applications such as retrieving objects from hazardous environments.

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Publications List

Journals : Peer reviewed

[1] Nuzrath Hameedha A, Yutaka Ishibashi, Konstantinos E. Psannis:
Effects of QoS control in remote master-slave robot systems with force feedback
International Journal of Mechanical Engineering and Robotics Research (IJMERR), vol. 10, no. 2, pp. 49-53, Feb. 2021.

[2] Nuzrath Hameedha A, Yutaka Ishibashi:
Effects of Local and Global adaptive Δ-causality control on cooperative work between remote robot systems with force feedback.
ITE Trans. Media Technology and Applications, vol. 10, issue 1, Jan. 2022.

Seminar

[1] Nuzrath Hameedha, Yutaka Ishibashi, Pingguo Huang, Yuichiro Tateiwa:
Cooperation between Remote robot systems with force feedback by using master-slave relation
IEEJ Tokai branch Young Scientists Seminar on "Information Communication and Signal Processing for Big Data Utilization," Sep. 2018.

Awards

[1] The 3rd World Symposium on Communication Engineering (WSCE), Best Student Paper Award, Oct. 2020. (Presentation only - contents in Journal [1])

[2] The 3rd World Symposium on Communication Engineering (WSCE), Best Oral Presentation Award, Oct. 2020. (Presentation only - contents in Journal [1])