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# Robust Bilateral Control with Internet Communication

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Abstract— Smith Predictor is a well-known method for compensating time delay in control systems. Therefore, it has been applied to many systems with time delay so far. However, delay time should be estimated precisely in this method. So, if time delay is fluctuant and unpredictable, like the communication delay over the Internet, performance of Smith Predictor deteriorates.

This paper proposes "Communication Disturbance Observer". It regards the error caused by time delay as disturbance torque (or acceleration), then it can observe and compensate the error. Furthermore, it doesn't need to estimate the value of delay time; therefore it can be applied to control systems with fluctuant and unpredictable time delay. It can be said that control system with "Communication Disturbance Observer" is robust to time delay and fluctuation of that.

Effectiveness and robustness of proposed method is shown by result of simulation and experiment. In experiment, master-slave manipulator was used over the Internet. We were able to get the sense of touch from the environment of remote site.

## I. Introduction

Due to the rapid progress of the Internet, global communication has become familiar. Therewithal, many researches about teleoperation have been carried out over the Internet. One of the destinations of that is to get the sense of touch from the environment of remote site. However, the sense of touch has not been applied for communication despite the extensive popularization of auditory sense and sense of sight as communication tool. Why does this situation occur? The answer is that teleoperation to get the sense of touch is very difficult.

The most popular method of teleoperation to get the sense of touch is using bilateral control system (with master and slave manipulator). And the most serious problem of teleoperation is existence of communication delay on the communication line. Communication delay in the communication system can be regarded as the time delay in the control system. Time delay in the system induces phase-delay, then it destabilizes the system. This is the reason why it is difficult to get the sense of touch in teleoperation system. In addition, particularly over the Internet, time delay is fluctuant. This makes the problem more difficult. Because of these difficulty (compensating communication delay), research of teleoperation with time delay has few perfectly confirmed method. So, many researchers have challenged to this difficult and attractive problem.

The pioneer of teleoperation, or compensating time delay is by Anderson and Spong[5]. They treated stability of system from the perspective of passivity and proposed passivity and scattering theory. Later, many researches of stability applied passivity to assure stability in teleoperation. Then, Niemeyer and Slotine proposed wave variables from the concept of passivity[6]. Furthermore wave variables were applied to teleoperation over the Internet ([7], [8]). Recently, bilateral teleoperation system with wave variables and Smith Predictor was proposed ([2], [4]).

In this paper, we propose Communication Disturbance Observer. It regards the error caused by time delay as disturbance torque on slave (Network Disturbance) and observes that. Advantage of it is that it doesn't need the value of delay time. Therefore it can keep robustness even if time delay is fluctuant and unpredictable. The effectiveness of this method is verified by simulation and experimental results. Experiment was carried out between Kawasaki (Japan) and Maribor (Slovenia) over the Internet. Distance between these two countries was about 9000km.

This paper is constructed as follows. Section II introduces Smith Predictor and shows how Smith Predictor compensates time delay. On the other hand, it shows that the effect of Smith Predictor deteriorates with fluctuant and unpredictable time delay. Section III proposes Communication Disturbance Observer and discusses design of observer gain. Section IV shows simulation results, and verifies the effectiveness of Communication Disturbance Observer under fluctuant and unpredictable time delay. Section V explains experimental setup and shows experimental results. Here in simulation and experiment, we used 1-DOF system to explain our method simply. In section VI, this paper is concluded.

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## II. Smith Predictor

Firstly, this section explains Smith Predictor briefly. Smith Predictor is a conventional method for the system with time delay. But if fluctuation of time delay exists in a system, its effectiveness deteriorates.

### A. Smith Predictor

Smith Predictor is a conventional method of compensating time delay. Communication delay in the teleoperation system is equivalent to time delay in the control system. So, it has been applied in many researches.

Fig. 1 is a simple control system with time delay ($C(s)$ : controller, $G(s)$ : plant). Closed-loop transfer function of

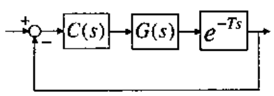


Fig. 1. Control system with time delay

this system $G_{cl}(s)$ is as follows.

$$G_{cl}(s) = \frac{C(s)G(s)e^{-Ts}}{1 + C(s)G(s)e^{-Ts}} \quad (1)$$

Here, characteristic polynomial $\Delta(s)$ is as follows.

$$\Delta(s) = 1 + C(s)G(s)e^{-Ts} \quad (2)$$

There is $e^{-Ts}$ in characteristic polynomial. This shows that time delay possibly affects stability of the system.

A control system (Fig. 1) with Smith Predictor is shown in Fig. 2. Closed-loop transfer function is (3)

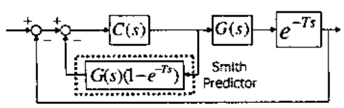


Fig. 2. Control system with time delay

$$G_{cl}(s) = \frac{C(s)G(s)}{1 + C(s)G(s)}e^{-Ts} \quad (3)$$

Then, characteristic polynomial is as follows.

$$\Delta(s) = 1 + C(s)G(s) \quad (4)$$

Here, time delay doesn't affect stability of the system anymore. This is the effectiveness of Smith Predictor.

### B. Fluctuation of Time Delay

It is shown that Smith Predictor is very effective to compensate the error caused by time delay in a system. However, sometimes time delay is fluctuant and unpredictable, particularly over the Internet. This phenomenon has prospects of deteriorating a system with Smith Predictor. If time delay is fluctuant (as Fig. 3), whole time delay will be indicated as follows.

$$T_d = T + \Delta T \quad (5)$$

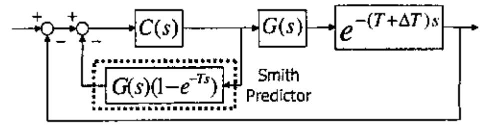


Fig. 3. Smith Predictor with fluctuant and unpredictable time delay

Then, closed-loop transfer function becomes as follows.

$$G_{cl}(s) = \frac{C(s)G(s)e^{-(T+\Delta T)s}}{1 + C(s)G(s) + C(s)G(s)e^{-Ts}(e^{-\Delta Ts} - 1)} \quad (6)$$

And, characteristic polynomial becomes as follows.

$$\Delta(s) = 1 + C(s)G(s) + C(s)G(s)e^{-Ts}(e^{-\Delta Ts} - 1) \quad (7)$$

From (7), it is found out that fluctuant and unpredictable time delay affect stability of the system, despite applying Smith Predictor. So, Smith Predictor is not useful in the system with fluctuant and unpredictable time delay.

### C. Smith Predictor in Bilateral System

At first, we consider a bilateral teleoperation system with time delay (Fig. 4). $T_1$ is time delay from master to

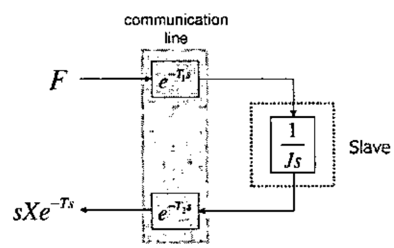


Fig. 4. Bilateral teleoperation system with time delay

slave, and $T_2$ is time delay of opposite direction. $J$ means the inertia of manipulator. Velocity information to master is affected by round trip time delay $T (T = T_1 + T_2)$. Then we apply Smith Predictor to the system shown in Fig. 4. The system with Smith Predictor is Fig. 5. Velocity

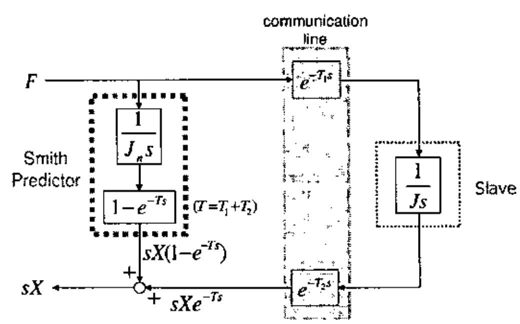


Fig. 5. Bilateral teleoperation system with time delay applying Smith Predictor

information to master is not affected by $T$ anymore.

## III. Communication Disturbance Observer

This section proposes Communication Disturbance Observer. This is a new method of compensating the error caused by time delay and have the same effect as Smith Predictor. Furthermore, even if time delay is fluctuant and unpredictable, the system keeps robustness. So, in this section, we explain Disturbance Observer briefly at first. Then the concept of Network Disturbance is introduced and Communication Disturbance Observer is proposed.

### A. Disturbance Observer

Disturbance Observer observes disturbance on control system. We will explain that briefly by using an actuating model of electric motor. Disturbance consists of load

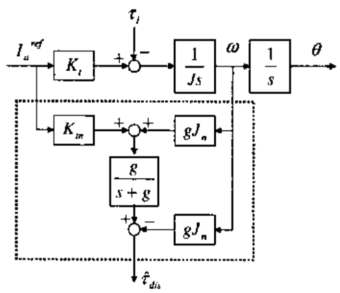


Fig. 6. Diagrammatic illustration of electric motor and Disturbance Observer

torque and variation of parameter.

$$\tau_{dis} = \tau_l + \Delta J s\omega - \Delta K_t I_a^{ref} \quad (8)$$

($\tau_l$ is load torque, $J$ is inertia of electric motor, $\omega$ is angular velocity, $K_t$ is torque coefficient and $I_a^{ref}$ is reference value of current) Disturbance Observer includes Low Pass Filter (LPF), so estimated disturbance is as follows

$$\hat{\tau}_{dis} = \frac{g}{s+g}\tau_{dis} \quad (9)$$

Here, LPF is set as first-order delay. As you can see, observer gain $g$ is hoped to be as large as possible for the purpose of making sensing bandwidth as broad as possible. By feedback of estimated disturbance, we can construct robust acceleration control system.

### B. Network Disturbance

Before introducing Communication Disturbance Observer, the concept of Network Disturbance is introduced. Here, we consider that the error of position information to master is caused by not time delay but disturbance torque (or acceleration) on slave $F(1-e^{-Ts})$. And we call this disturbance as Network Disturbance. Here, Fig. 4 is considered as Fig. 7.

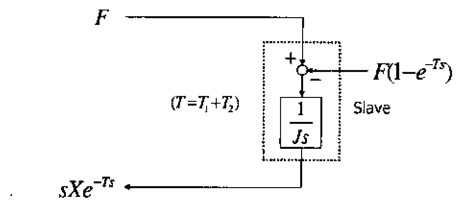


Fig. 7. Considering time delay as disturbance on slave

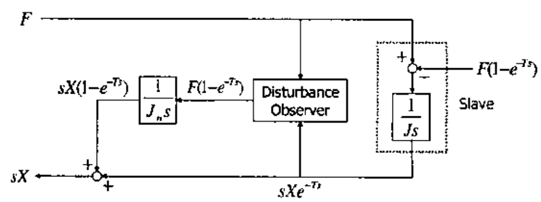


Fig. 8. The effectiveness of Communication Disturbance Observer

### C. Communication Disturbance Observer

Communication Disturbance Observer observes Network Disturbance. In Fig. 8, we can find Communication Disturbance Observer have the same effect as Smith Predictor (refer to Fig. 5). Furthermore, Communication Disturbance Observer does not need the value of delay time. So, even if time delay is fluctuant and unpredictable, the effectiveness of that never deteriorates.

### D. Design of Observer Gain

Though we do not describe in Fig. 8, there is also disturbance on slave, and there is disturbance observer of slave (Fig. 9). Furthermore, both of them include LPF. So whole disturbance torque ($F_{disnet}$) that Communication Disturbance Observer observes is actually as follows.

$$F_{disnet} = \frac{g_{net}}{s+g_{net}}F(1-e^{-Ts}) + \frac{g_{net}}{s+g_{net}}\frac{s}{s+g_d}F_{dis} \quad (10)$$

($g_{net}$ is the gain of Communication Disturbance Observer, $g_d$ is the gain of Disturbance Observer on slave) There

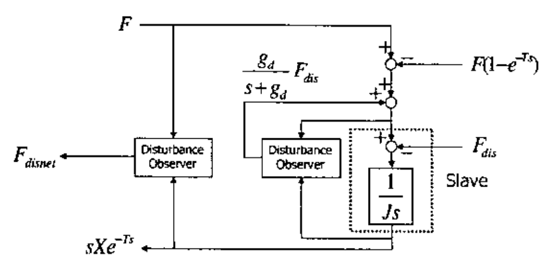


Fig. 9. Considering disturbance and disturbance observer of slave

are two terms in right-hand side of (10), and we have two purposes on designing observer gain. Firstly, we want to observe only $F(1 - e^{-Ts})$. So, we want the second term to be as follows.

$$\frac{g_{net}}{s + g_{net}} \frac{s}{s + g_d} F_{dis} \to 0 \tag{11}$$

In other words, we want $G(s) = \frac{g_{net}}{s+g_{net}} \frac{s}{s+g_d}$ to be 0 in almost all bandwidth. Then, we calculated $G(s)$ in two cases ($g_{net} < g_d$ and $g_d < g_{net}$). The results are shown in Fig. 10 and Fig. 11(here $G_{net} = \frac{g_{net}}{s+g_{net}}$, $G_d = \frac{s}{s+g_d}$).

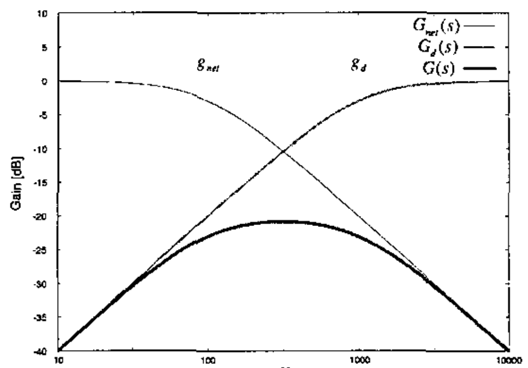


Fig. 10. Gain of $G(s)$ ($g_{net} = 100$, $g_d = 1000$)

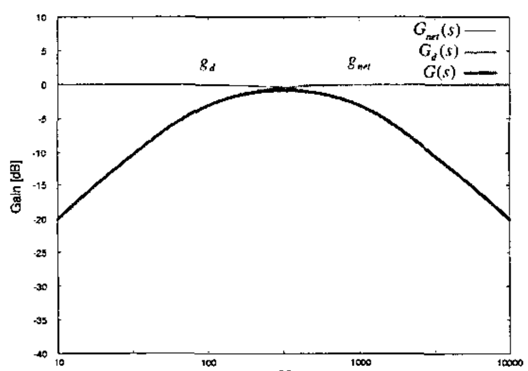


Fig. 11. Gain of $G(s)$ ($g_d = 100$, $g_{net} = 1000$)

To fulfill a demand of (11), gains should be designed as follows

$$g_{net} \leq g_d \tag{12}$$

Here, we must remember there is the other purpose. The purpose is that $F(1 - e^{-Ts})$ should be observed as precise as possible. So, bandwidth of LPF ($\frac{g_{net}}{s+g_{net}}$) should be wider. In other words, gain of LPF ($g_{net}$) is hoped to be as large as possible. Consequently, observer gains should be designed as follows

$$g_{net} = g_d \tag{13}$$

## IV. Simulation

This section shows the effectiveness of Communication Disturbance Observer comparing with Smith Predictor. As described in section III, Communication Disturbance Observer can keep robustness of the system with time delay, even if time delay is fluctuant and unpredictable. So, simulation comparing Smith Predictor and Communication Disturbance Observer under fluctuant and unpredictable time delay was carried out. Virtual round trip time was implemented at random in the range of $220ms \leq T \leq 460ms$. And we did simulations in 3 cases. Applying Smith Predictor with small model of delay time ($T = 220ms$), with large model of delay time ($T = 460ms$), and applying Communication Disturbance Observer. In other words, the situation that time delay is fluctuant and unpredictable is assumed. Therefore the model of delay time in Smith Predictor is not accurate. The results are shown in Fig. 12, Fig. 13 and Fig. 14(thick line indicates master, thin line is slave). We can find that the cases applied Smith Predictor with inaccurate model of delay time have larger position error and feel more inertia comparing with the case applied Communication Disturbance Observer. And another advantage of using Communication Disturbance Observer is that we don't need the value of delay time.

## V. Experiment

Master and slave manipulator are shown in Fig. 15 and Fig. 16 respectively. The distance between two manipulators is about 9000km. Both of them are 1-DOF rotary

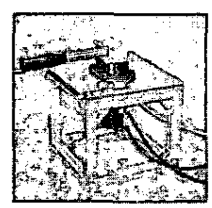

Fig. 15. Manipulator in Kawasaki (Japan)

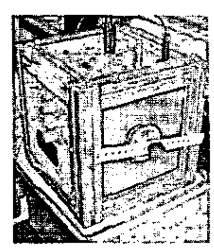

Fig. 16. Manipulator in Maribor (Slovenia)

robots. Both arms are 16cm length. Two manipulators are connected over the Internet using TCP/IP protocol. Condition of one way delay time is shown in Fig. 17. In experiment, we manipulated master manipulator in

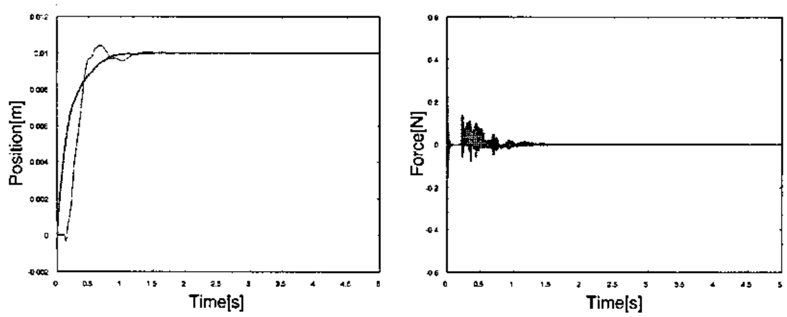


Fig. 12. Applying Smith Predictor with small model of delay time ($T = 220ms$).

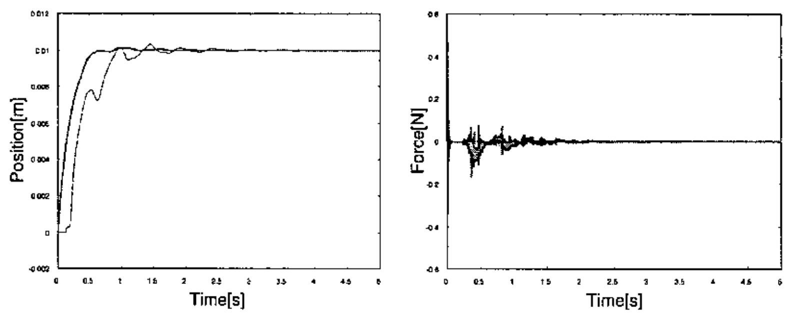


Fig. 13. Applying Smith Predictor with large model of delay time ($T = 460ms$).

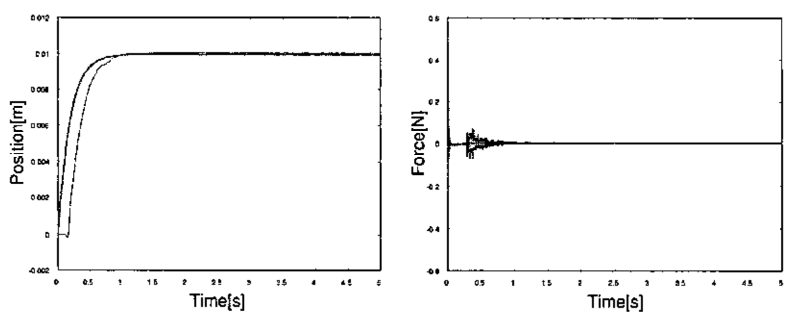


Fig. 14. Applying Communication Disturbance Observer.

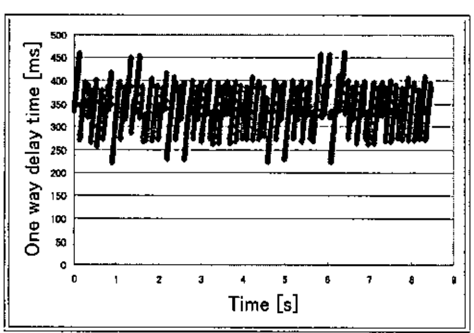


Fig. 17. One way delay time data

Japan and then, slave manipulator contacted with the environment in Slovenia. Experimental results are shown in Fig. 18 and Fig. 19(thick line indicates master, thin line is slave, and dashed circle shows contact motion). Reverse sign of master torque and slave torque is attributed to the law of action and reaction. From two results, it was found out that both manipulators stably follow each other in free motion. However in contact motion, though the system with Communication Disturbance Observer could get the information of contact force, the system with Smith Predictor couldn't. Therefore we can say that Communication Disturbance Observer is a valid method in the system with fluctuant and unpredictable time delay

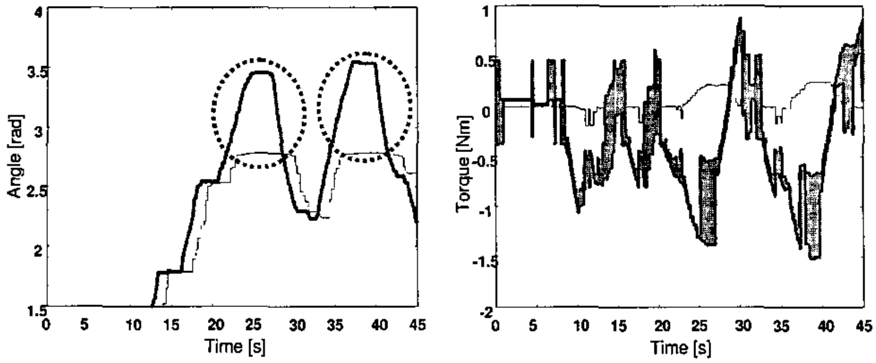


Fig. 18. Bilateral teleoperation with Smith Predictor

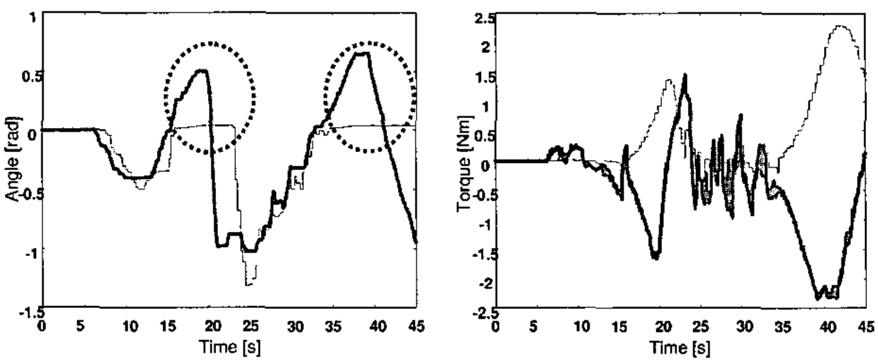


Fig. 19. Bilateral teleoperation with Communication Disturbance Observer

(like the Internet).

## VI. Conclusion

In this paper, Communication Disturbance Observer was proposed. For compensating the error caused by time delay, Smith Predictor was conventionally used so far. But regarding the error caused by time delay as disturbance torque on slave (Network Disturbance) and observing that, Communication Disturbance Observer can have the same effect as Smith Predictor. Furthermore, it doesn't need precise model of delay time, so if time delay is fluctuant and unpredictable, the effectiveness of it never deteriorates. In other words, the use of Communication Disturbance Observer can make bilateral teleoperation system very robust to time delay and fluctuation of that. The effectiveness of Communication Disturbance Observer was verified by simulation and experimental results. We were also able to get the sense of touch from the long-distance remote environment.

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