# Time Delay Compensation by Communication Disturbance Observer in Bilateral Teleoperation Systems

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***Abstract*— In a research area of bilateral teleoperation systems, time delay generated in communication line is one of very serious problems. Time delay in control systems induces severe phase delay. Then the phase delay possibly destabilizes the system and deteriorates performance of the system. Therefore many studies about time delay in bilateral teleoperation systems have been conducted so far. Some researches have accomplished stabilization method or compensation method of constant time delay. However compensation of time-varying or fluctuant time delay has not been completed.**

**This paper introduces a novel compensation method of time delay. The method is based on the concept of network disturbance (ND) and communication disturbance observer (CDOB). CDOB estimates ND and estimated value is utilized for the compensation of time delay. In addition, because it does not need delay time model, it can be applied to systems with time-varying or fluctuant time delay. Furthermore the method is very simple and it is very easy to implement. The effectiveness of the proposed method is verified by simulation and experimental results.**

## I. Introduction

Recently rapid development of information technology gives people comfortable life. People can obtain much information and communicate with colleagues all over the world. From the viewpoint of industrial and academic situation, it makes a big contribution to advanced technologies like computers, communications, robotics, and so on. However it should be noted that most of these kind of information except for data transmission is only for visual and auditory sensation.

Human beings primitively have five sensations. Those are visual, auditory, tactile, smell and taste sensations. When human perceives an object, the perception becomes more distinct with many kinds of sensations. In such a background, transmission of tactile sensation has recently received keen attention. However it has not been realized so far because tactile sensation is basically bidirectional information. In other words, tactile sensation is based on the law of action and reaction. Then bilateral control and very fast communication are necessary for reproduction of tactile sensation. Time delay generated in communication line is therefore a very serious problem for transmission of vivid tactile sensation. Time delay possibly destabilizes bilateral control systems and deteriorates performance of that. Consequently many researches of bilateral control systems with time delay (bilateral teleoperation systems) have been conducted.

The first systemized stabilization method of bilateral teleoperation systems was proposed by Anderson and Spong [1]. They discussed stability of systems from the perspective of passivity and formulated stabilization method using scattering matrix. Then Niemeyer and Slotine extended the method and proposed wave variables [2]. These passivity-based stabilization methods have been utilized in many cases since then. Meanwhile Smith predictor [3] that was proposed for compensation of time delay in common time delay systems have also been used for bilateral teleoperation systems. However it should be noted that these works do not consider time-varying or fluctuant time delay. Consequently researches in case of time-varying or fluctuant time delay have also been conducted so far.

Most of those researches are based on passivity-based theory. Kosuge et al. proposed "virtual time delay method" and combined it with scattering transformation [4]. Niemeyer and Slotine extended wave variable formalism to the situation of variable time delay. Yokokohji et al. proposed a compensation of position drifts due to the time-varying delay utilizing standard delay time [6]. Furthermore energy balance monitor is proposed and implemented to the method [7]. Munir and Book utilized modified Smith predictor, a Kalman filter and energy regulator in the wave variable framework [8]. Besides, there are some studies using robust control theory ($H_\infty$ control theory). Leung et al. regarded the difference between delayed communication line and nominal communication line as an uncertainty and designed the controller based on $\mu$-synthesis [9]. Sano et al. also designed the control system utilizing the $H_\infty$ design framework [10].

In this paper, a novel compensation method of time delay in bilateral teleoperation systems is introduced. As authors presented in earlier papers, the method is based on the concept of network disturbance (ND) and communication disturbance observer (CDOB) [11], [12]. CDOB estimates ND and estimated value is utilized for the compensation of time delay. In this method, delay time model is not necessary. It is therefore able to be applied to systems with time-varying or fluctuant time delay. Furthermore the structure is very simple and it is easy to implement. In addition to earlier work, this paper makes mention of design procedure of CDOB and validity of ND estimation. The effectiveness of the method is verified by simulation and experimental results.

This paper is organized as follows. At first in section II,

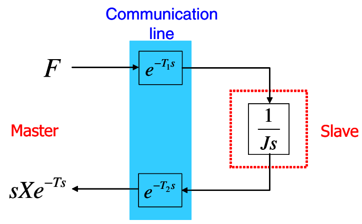



Fig. 1. An example of bilateral teleoperation system

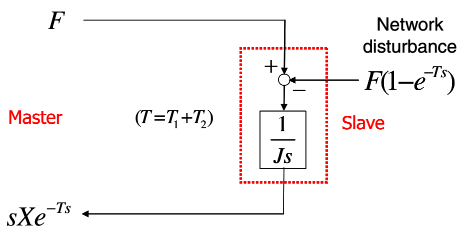



Fig. 2. Concept of network disturbance

the concept of ND is introduced. Then in section III, brief overview of CDOB, design of CDOB, a time delay compensation method and design of cutoff frequency are described. The validity of the proposed method is verified by simulation and experimental results in section IV and V, respectively. Finally in section VI, this paper is concluded.

## II. Network Disturbance (ND)

This section presents the concept of network disturbance (ND) [11], [12]. Firstly an example of a bilateral teleoperation system is illustrated and introduced briefly. Then the notion of ND is presented and formulation of ND is conducted.

### A. Time Delay in Bilateral Teleoperation Systems

Fig. 1 is an example of bilateral teleoperation system. $T_1$ means time delay from master side to slave side and $T_2$ is time delay from slave side to master side. $F$ is a control input of slave (force or torque dimension) and $sXe^{-Ts}$ is a delayed feedback signal (velocity dimension) to master. Time delay generated in communication line makes feedback signal delayed relative to control input. It leads to phase delay of the system and destabilization. Because of distinctive characteristics of time delay, it is difficult to compensate time delay effect or to stabilize the system.

### B. Network Disturbance (ND)

At this moment, Fig. 1 is reconsidered. In this figure, feedback signal is delayed relative to control input of slave. As mentioned before, this situation is induced by time delay existing in communication line. However from the viewpoint of master side, it can be assumed that feedback signal is delayed by not time delay but hypothetical disturbance as shown in Fig. 2 ($T$ means round trip delay time : $T = T_1+T_2$). In other words, the hypothetical disturbance exerted on slave delays feedback signal. This disturbance is defined as ND

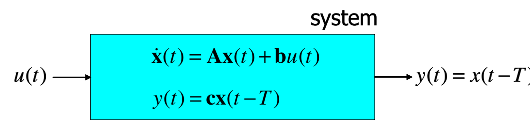



Fig. 3. A linear system with time delay

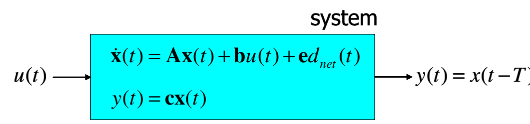



Fig. 4. A linear system with network disturbance

($D_{net}(s)$ or $d_{net}(t)$). It is formulated in both Laplace domain and time domain as follows.

$$D_{net}(s) = F(1 - e^{-Ts}) \quad (1)$$

$$d_{net}(t) = f(t) - f(t - T) \quad (2)$$

This is the basic concept of this research.

## III. Compensation of Time Delay

In this section, time delay compensation method based on communication disturbance observer (CDOB) is introduced. At first, basic structure and design of CDOB are presented in a situation of general linear systems [12]. Then estimation of network disturbance by CDOB is demonstrated by simulation results. It can estimate ND even if time delay is time-varying or fluctuant. Furthermore comparison between zero order CDOB and first order CDOB is also conducted. Then compensation method of time delay based on CDOB is introduced and a design method of cutoff frequency of CDOB considering disturbance exerted on slave is described in a situation of bilateral teleoperation systems [11].

### A. Communication Disturbance Observer (CDOB)

The structure of CDOB is the same as disturbance observer (DOB) [13], [14]. In fact, CDOB is a DOB for the estimation of ND. Fig. 3 is a linear system with time delay. For simplicity, it is assumed that there is only output delay. The state equation and the output equation of the system are described as follows.

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{b}u(t) \quad (3)$$

$$y(t) = \boldsymbol{c}\boldsymbol{x}(t - T) \quad (4)$$

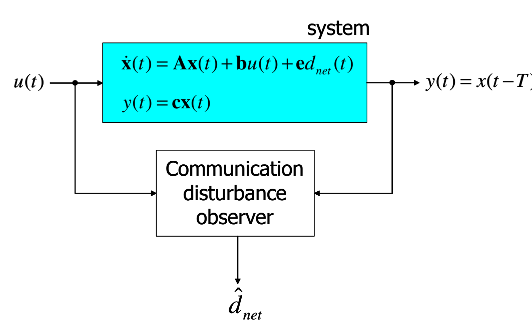



Fig. 5. Schematic diagram of CDOB

In this case, ND is computed as below.

$$d_{net}(t) = u(t) - u(t-T) \tag{5}$$

Then the state equation and the output equation in case of considering ND are as follows.

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{b}u(t) + \boldsymbol{e}d_{net}(t) \tag{6}$$

$$y(t) = \boldsymbol{c}\boldsymbol{x}(t) \tag{7}$$

The system is shown in Fig. 4. Though output of the system is delayed relative to input, there is no time delay in the system. Instead of time delay, there exists ND. Then ND is estimated by CDOB as shown in Fig. 5.

### B. Design of CDOB

From here, design of CDOB is described. Generally observer estimates observable state variables. Therefore state equation and output equation should be transformed in order to treat disturbance as an observable state variable. Then a differential equation of ND should be installed. For that purpose, property of ND is discussed at first. The delayed input $u(t-T)$ expanded using Taylor expansion is described as below.

$$u(t-T) = u(t) - Tu'(t) + \frac{1}{2!}T^2u''(t) - \cdots \tag{8}$$

Then from (5), ND is approximated as follows.

$$\begin{aligned} d_{net}(t) &= u(t) - u(t-T) \\ &= Tu'(t) - \frac{1}{2!}T^2u''(t) + \cdots \end{aligned} \tag{9}$$

In case that input $u(t)$ is approximated as power series described in the next equation,

$$u(t) = p_0 + p_1t + p_2t^2 + \cdots + p_nt^n \tag{10}$$

ND is expanded into power series shown as below.

$$\begin{aligned} d_{net}(T,t) = q_0(T) + q_1(T)t + q_2(T)t^2 + \cdots \\ \cdots + q_{n-1}(T)t^{n-1} \end{aligned} \tag{11}$$

The approximated ND is high order polynomial of 't'. Furthermore in case that time delay is time-varying or fluctuant, it is approximated as follows.

$$T(t) = r_0 + r_1t + r_2t^2 + \cdots + r_mt^m \tag{12}$$

Consequently ND is approximated as follows.

$$d_{net}(t) = s_0 + s_1t + s_2t^2 + \cdots + s_{n+m-1}t^{n+m-1} \tag{13}$$

The approximation becomes higher order polynomial. It is therefore more difficult to estimate ND precisely. A high order observer should be utilized for estimation of state variable approximated as high order polynomial. However a high order observer is generally very complex and effect of noises becomes larger. Therefore performance of different order observers should be compared. Then the performance of zero order CDOB for ND estimation is compared with that of first order CDOB here. Firstly ND vector is set as below.

$$\boldsymbol{d}_{net}(t) = \begin{bmatrix} \dot{d}_{net}(t) \\ d_{net}(t) \end{bmatrix} \tag{14}$$

Then following differential equations are introduced in each case.

[zero order CDOB]

$$\dot{d}_{net}(t) = 0 \tag{15}$$

[first order CDOB]

$$\ddot{d}_{net}(t) = 0 \tag{16}$$

The state equation and the output equation are accordingly transformed as follows.

$$\begin{bmatrix} \dot{\boldsymbol{x}}(t) \\ \dot{\boldsymbol{d}}_{net}(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{E} \\ \boldsymbol{O} & \boldsymbol{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(t) \\ \boldsymbol{d}_{net}(t) \end{bmatrix} + \begin{bmatrix} \boldsymbol{b} \\ \boldsymbol{o} \end{bmatrix} u(t) \tag{17}$$

$$y(t) = \begin{bmatrix} \boldsymbol{c} & \boldsymbol{o} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(t) \\ \boldsymbol{d}_{net}(t) \end{bmatrix} \tag{18}$$

Here $\boldsymbol{D}$ is derived as follows.

[zero order CDOB]

$$\boldsymbol{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{19}$$

[first order CDOB]

$$\boldsymbol{D} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \tag{20}$$

Then CDOB is set up as follows.

$$\begin{aligned} \begin{bmatrix} \dot{\hat{\boldsymbol{x}}}(t) \\ \dot{\hat{\boldsymbol{d}}}_{net}(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{E} \\ \boldsymbol{O} & \boldsymbol{D} \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{x}}(t) \\ \hat{\boldsymbol{d}}_{net}(t) \end{bmatrix} + \begin{bmatrix} \boldsymbol{b} \\ \boldsymbol{o} \end{bmatrix} u(t) \\ + \boldsymbol{k}\big(y(t) - \hat{y}(t)\big) \end{aligned} \tag{21}$$

$$\hat{y}(t) = \begin{bmatrix} \boldsymbol{c} & \boldsymbol{o} \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{x}}(t) \\ \hat{\boldsymbol{d}}_{net}(t) \end{bmatrix} \tag{22}$$

Estimated ND ($\hat{d}_{net}$) of both cases are computed as follows.

[zero order CDOB]

$$\hat{d}_{net} = \frac{g_{net}}{s + g_{net}} d_{net} \tag{23}$$

[first order CDOB]

$$\hat{d}_{net} = \frac{k_1}{s^2 + k_2s + k_1} d_{net} \tag{24}$$

In (23), $g_{net}$ means cutoff frequency of low pass filter in zero order CDOB. Meanwhile, $k_1$ and $k_2$ are parameters of second order low pass filter in first order CDOB and meanings of those in second order systems are described as follows.

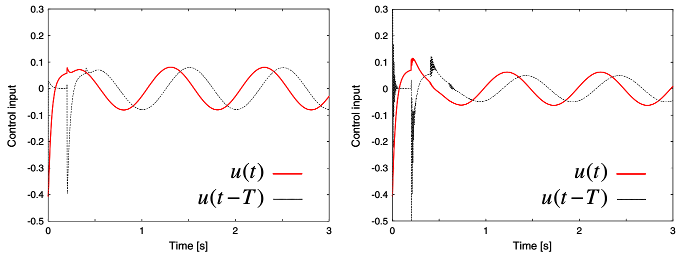
$$k_1 = \omega_n^2 \tag{25}$$

$$k_2 = 2\zeta\omega_n \tag{26}$$

Here $k_1$ and $k_2$ are set as follows for comparison with zero order CDOB.

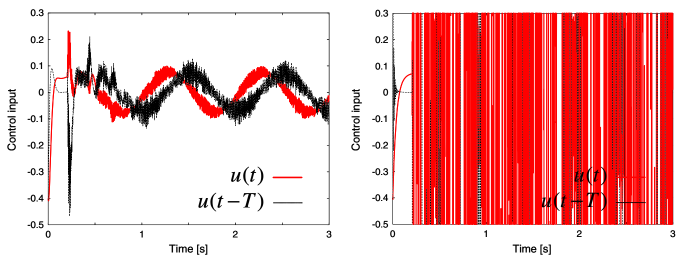
$$k_1 = g_{net}^2 \tag{27}$$

$$k_2 = 0.25g_{net} \tag{28}$$




(a) zero order CDOB (b) first order CDOB

Fig. 6. Estimation of ND by CDOB (constant delay)




(a) zero order CDOB (b) first order CDOB

Fig. 7. Estimation of ND by CDOB (fluctuant delay)

For the comparison of two kinds of CDOBs, simulation of ND estimation is conducted. Figs. 6 (a) and 6 (b) show ND estimation results in case of constant time delay ($T = 200ms$). In these figures, delayed input $u(t-T)$ (this value is computed only for verification of CDOB) is calculated utilizing control input value $u(t)$ and estimated ND $d_{net}(t)$ as the next equation.

$$u(t-T) = u(t) - d_{net}(t) \tag{29}$$

From these figures, ND estimation in case of zero order CDOB is more precise than that in case of first order CDOB. Meanwhile, Figs. 7 (a) and 7 (b) illustrate ND estimation results in case of fluctuant time delay ($200ms \leq T \leq 220ms$). The estimated ND by zero order CDOB is noisier than that of first order CDOB.

From these results, zero order CDOB is more effective than first order CDOB for ND estimation. Zero order CDOB is therefore adopted in subsequent part of this paper.

### C. Time Delay Compensation in Bilateral Teleoperation Systems

CDOB can be applied to bilateral teleoperation systems like a system shown in Fig. 1 or 2. In case that next ideal condition

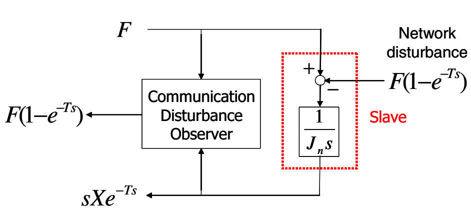



Fig. 8. CDOB in bilateral teleoperation systems

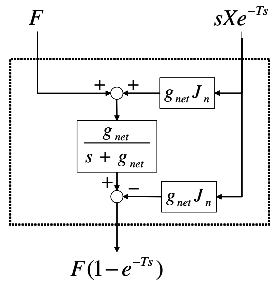



Fig. 9. Internal structure of CDOB

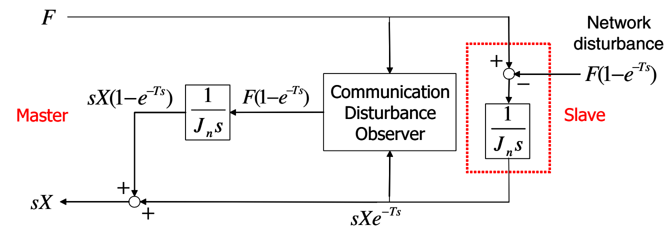



Fig. 10. Compensation of time delay

is assumed ($J_n$ means nominal moment of inertia),

$$\begin{aligned} g_{net} &\longrightarrow \infty \\ J &= J_n \end{aligned}$$

CDOB in bilateral teleoperation systems is shown as Fig. 8 and internal structure of that is shown in Fig. 9. Estimated ND is utilized for compensation of time delay. The illustration of compensation is shown in Fig. 10. Feedback signal is not delayed any more in Fig. 10. As mentioned before, ND can be estimated by CDOB even if time delay is time-varying or fluctuant. Therefore time delay can be compensated even if time delay is time-varying or fluctuant.

### D. Design of cutoff Frequency

In actual bilateral teleoperation systems, disturbance exerted on slave or disturbance observer applied to slave can not be ignored. In other words, those elements affect the estimation of ND. Fig. 11 shows the effect. Then the value estimated by CDOB ($F_{disnet}$) is derived as follows.

$$F_{disnet} = \frac{g_{net}}{s+g_{net}} F(1-e^{-Ts}) + \frac{g_{net}}{s+g_{net}} \frac{s}{s+g_d} F_{dis} \tag{30}$$

Here $g_d$ means cutoff frequency of disturbance observer and $F_{dis}$ is disturbance exerted on slave. The equation indicates

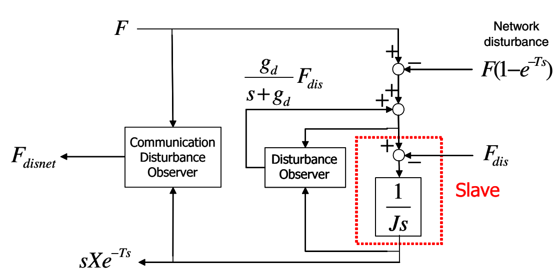
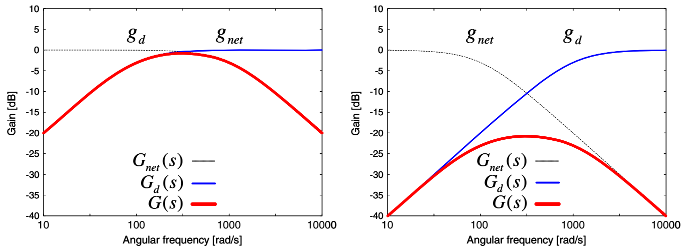



Fig. 11. Consideration of disturbance exerted on slave




(a) $g_d < g_{net}$ (b) $g_{net} < g_d$

Fig. 12. Gain diagrams of $G(s)$

that estimated value by CDOB ($F_{disnet}$) includes not only ND but also disturbance exerted on slave. However the estimated value ideally should be as follows.

$$F_{disnet} \longrightarrow F(1 - e^{-Ts}) \tag{31}$$

In order to fulfill the condition (31), two conditions described as follows are necessary in almost all bandwidth.

$$\frac{g_{net}}{s + g_{net}} \longrightarrow 1 \tag{32}$$

$$\frac{g_{net}}{s + g_{net}} \frac{s}{s + g_d} \longrightarrow 0 \tag{33}$$

Then design procedure of cutoff frequencies ($g_{net}$, $g_d$) considering (32) and (33) is presented in what follows.

At first, the first demand derived from (32) is as below.

[demand1] $g_{net} \longrightarrow \infty$

Next the condition of (33) is considered. For smooth discussion of following part, three transfer functions are set as follows.

$$G_{net}(s) = \frac{g_{net}}{s + g_{net}} \tag{34}$$

$$G_d(s) = \frac{s}{s + g_d} \tag{35}$$

$$G(s) = \frac{g_{net}}{s + g_{net}} \frac{s}{s + g_d} \tag{36}$$

Due to the condition of (33), magnitude of $G(s)$ should ideally be small without limit in almost all bandwidth. Then a gain diagram in case of $g_d < g_{net}$ and that in case of $g_{net} < g_d$ are compared here. Gain diagrams of three transfer functions ($G_{net}(s)$, $G_d(s)$ and $G(s)$) are shown in Figs. 12 (a) and 12 (b). The magnitude of $G(s)$ in case of $g_{net} < g_d$ is smaller than that of $g_d < g_{net}$ in almost all bandwidth. Therefore the second demand derived by (33) is described as follows.

[demand2] $g_{net} \leq g_d$

Considering [demand1] and [demand2] simultaneously, cutoff frequencies should be designed as follows.

$$g_{net} = g_d \tag{37}$$

## IV. Simulation

In order to verify the effectiveness of proposed method, simulation was conducted. It is assumed that master and slave manipulators are 1DOF linear actuators. Parameters used in simulation are shown in Table. I. Fig. 13 shows position response in case of constant time delay ($T_1 = T_2 = 200ms$). The system is not destabilized by time delay and slave manipulator precisely tracks the motion of master manipulator. On the other hand, position response in case of time-varying or fluctuant time delay ($200ms \leq T_1, T_2 \leq 220ms$) is shown in Fig. 14. Though position response of slave slightly fluctuates, the system is stable. These results prove that proposed method is effective even if time delay is time-varying or fluctuant.

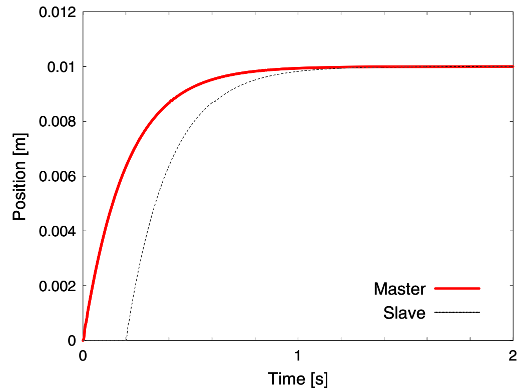



Fig. 13. Position response ($T_1 = T_2 = 200ms$ : constant)

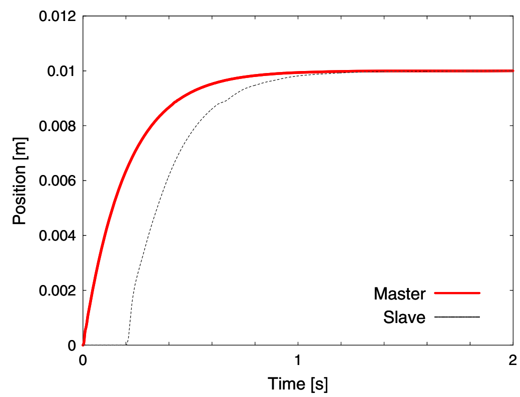



Fig. 14. Position response ($200ms \leq T_1, T_2 \leq 220ms$ : fluctuant)

## V. Experiment

For the verification of the effectiveness of proposed method, a bilateral teleoperation experiment using 1DOF rotary manipulator shown in Fig. 15 is executed. Parameters for the experiment are shown in Table. II. One way delay time $T_1$,

TABLE I
Parameters for simulation

| | | |
|---|---|---|
| $J_n$ | Nominal mass | 0.12 $kg$ |
| $K_t$ | Torque coefficient | 10.83 N/A |
| $K_p$ | Position gain | 900.0 |
| $K_v$ | Velocity gain | 60.0 |
| $K_f$ | Force gain | 50.0 |
| $g_{net}$ | Cutoff frequency of CDOB | 600.0 rad/s |
| $g_d$ | Cutoff frequency of DOB | 600.0 rad/s |

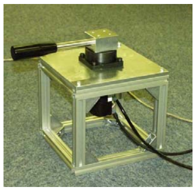


Fig. 15. 1DOF rotary manipulator

TABLE II
PARAMETERS FOR EXPERIMENT

| | | |
|---|---|---|
| $J$ | Moment of inertia | 0.00535 $kgm^2$ |
| $l$ | Arm length | 0.16 m |
| $G_r$ | Reduction gear ratio | 1/33 |
| $K_p$ | Position gain | 100.0 |
| $K_v$ | Velocity gain | 20.0 |
| $K_f$ | Force gain | 30.0 |
| $g_{net}$ | Cutoff frequency of CDOB | 40.0 rad/s |
| $g_d$ | Cutoff frequency of DOB | 40.0 rad/s |

$T_2$ are set as 200ms and generated in software program. Figs. 16 and 17 show position and force response, respectively. The system is not destabilized by time delay. Though there is some amount of position error, slave manipulator tracks the motion of master well. In addition, force transmission is achieved precisely. Therefore it can be found out that time delay is compensated correctly. The validity of proposed method is verified by experimental results.

## VI. CONCLUSION

This paper presented a novel compensation method of time delay in bilateral teleoperation systems. The method is based on the concept of network disturbance (ND) and communication disturbance observer (CDOB). The advantage of the method is that it is applicable to the system with time-varying or fluctuant time delay. Furthermore the method is very simple and it is easy to implement. The validity of it was verified by simulation and experimental results.

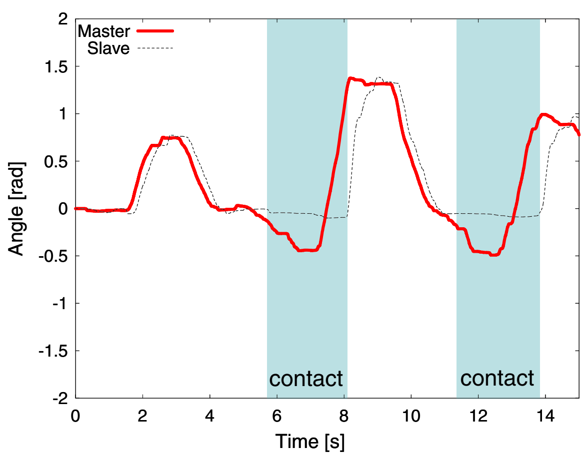



Fig. 16. Position response

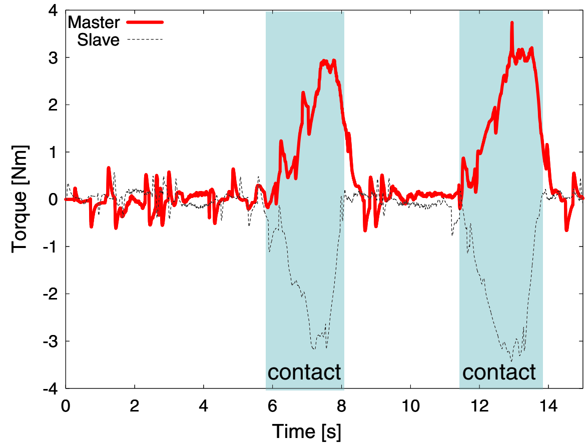



Fig. 17. Force response

### *Acknowledgments*

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