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Design and implementation of a modified communication disturbance observer for teleoperation systems

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Abstract: In this paper, a novel structure for a communication disturbance observer in teleoperation systems is proposed to achieve robust stability. A time delay compensation method based on the concept of network disturbance and a communication disturbance observer (CDOB) has been proposed in past research. Unlike model-based approaches, it works without a time delay model. Therefore, it can be implemented in teleoperation systems with unknown and time-varying delay. However, it has been observed that the system model errors and external disturbances seriously affect the steady-state characteristics. Hence, in this paper, to achieve robustness against disturbance and model uncertainty, the structure of the conventional CDOB is modified and a new structure for the CDOB in teleoperation systems is proposed, which uses the slave's delayed torque instead of its delayed position for time delay compensation. The desired transient response characteristic is achieved by designing the controller parameters. The time delay in the communication channel has been simulated by PCs in past studies, but in this paper, by implementing the communication channel through the TCP/IP protocol in the experimental setup, the effectiveness of the proposed structure is studied in the presence of real time delay and compared with the Smith predictor, the conventional CDOB, and other structures of CDOBs.

Key words: Time delay, teleoperation systems, network disturbance, stability, communication disturbance observer

1. Introduction

Due to nonminimum phase characteristics, time delay in the communication channel of teleoperation systems deteriorates the performance and destabilizes the system [1]. This problem is more complicated when the time delay is unknown and unpredictable, as in the case of Internet communications. Hence, the time delay effect on the performance of teleoperation systems has been investigated in some studies [2].

Anderson and Spong presented a passivity-based approach that uses scattering theory to stabilize teleoperation systems [3]. A wave variable method to reduce constant time delay effect in teleoperation systems was proposed by Niemeyer and Slotine [4]. Other approaches like robust control [5], sliding mode control [6,7], model predictive control [8], and Lyapunov-based control designs [9] have been studied to solve the time delay problem to date. Moreover, PID controller design is a discussed topic in the field of time-delayed systems [10]. In order to compensate the time delay effect on tactile transmission in teleoperation systems, local models of remote environments were studied in [11]. The proper performance of robot-assisted rehabilitation systems was also considered in [12]. The most famous time delay compensation method is the Smith predictor [13], which stabilizes time-delayed systems by using the predicted output signal of the controlled system. The method uses

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both a time delay model and a controlled system model; thus, model mismatch affects the stability of the system [14]. In addition, when there are no predictable or exact time delay models, the performance often deteriorates, e.g., in IP networks. That makes the Smith predictor unbefitting in compensation of unknown time delays. Natori et al. presented a novel time delay compensation method based on the concept of network disturbance (ND) and a communication disturbance observer (CDOB) [15,16]. In this method, the effect of time delay is supposed as force disturbance and estimated using a disturbance observer (DOB). This method compensates time delay effect without a time delay value or model. Therefore, it can be applied to systems with unknown and time-varying delay like network-based control systems or teleoperation systems that use the Internet as a communication channel [17]. However, there are some defects in the performance of this conventional CDOB. For example, the conventional CDOB requires the model of the controlled system for accurate estimation and model uncertainty generates other kinds of force disturbances. This method is not robust to model uncertainty and external disturbances. Therefore, system model errors and disturbances affect the steady-state characteristics [18].

In [19], it was proved that the stability of the system depends on the value of the cutoff frequency of the low-pass filter (LPF) in the CDOB. The value should be large enough for the system to be stable, while this is not possible in all devices. In [20], by adding a block to the feedback loop, a novel structure of time-delayed control systems with a communication disturbance observer was proposed in which the stability does not depend on the value of the cutoff frequency, but there is still steady-state error due to system model errors. In [21], a simple approach for reducing steady-state error in time-delayed systems was proposed, in which system models were designed as different values, while in the conventional method those system models were designed as similar values. In this method, steady-state error is reduced depending on the designed values. However, this method is only efficient in small time delays for teleoperation systems and large time delays in communication channels, making the system unstable. In [18] a new structure of CDOB was proposed to achieve the robustness of time-delayed control systems against system model errors and in [22] disturbance elimination characteristics of this structure were studied. In this new structure, the estimated network disturbance for time delay compensation is obtained from delayed system input instead of system output and thus the effect of model uncertainty between the model and plant on estimation is eliminated. For applying this structure to teleoperation systems, master torque can be considered as system input, but the delayed system input should be calculated properly. Hence, applying the structure in [18] to teleoperation systems does not provide desirable performance. In view of the problems mentioned for the conventional CDOB, this paper proposes another structure for the CDOB in teleoperation systems by considering model uncertainty. In the proposed structure, by calculating the slave's delayed torque from its delayed position, network disturbance is estimated from the master torque and the slave's delayed torque; thus, model uncertainty does not affect ND estimation and steady-state error. The external disturbance effect is also eliminated. On the other hand, stability of the proposed structure is independent of the cutoff frequency of the LPF. In this paper, by using master and slave models on two separate PCs, a communication channel is implemented through the TCP/IP protocol. The validity of the proposed method is verified by experimental results under real-time delay condition.

The rest of this paper is organized as follows: the effect of time delay in teleoperation systems is studied in Section 2. Section 3 introduces the concept of ND in teleoperation systems. Section 4 studies the effect of model uncertainty and disturbance on the conventional CDOB. The proposed structure for the CDOB in teleoperation systems and its advantages are presented in Section 5. The stability of the proposed structure is also analyzed. Experimental results to demonstrate the effectiveness of the proposed method compared with the Smith predictor and some structures of CDOBs in previous studies are illustrated in Section 6. Finally, the overall results of the paper are concluded.

2. Effect of time delay in teleoperation systems

Figure 1 shows a bilateral teleoperation system generally with time delay in the communication channel. According to the transmitted signals between the master and the slave, various bilateral teleoperation systems can be designed. In this paper, the control signal for the slave robot is generated at the master side, while the position information of the slave is sent back to the master. Therefore, the system in this paper is bilateral teleoperation with position feedback. Moreover, in the designed structure, the force is applied to the master robot; however, the main objective is to reach the desired position predefined by the user. In Figure 1, $R(s)$, $U(s)$, and $Y(s)$ are reference input, control input, and output, respectively, where the reference input is supposed to be the desired position and the output is the slave's position. $C(s)$ and $G(s)$ are the controller and transfer functions of the robots, respectively.

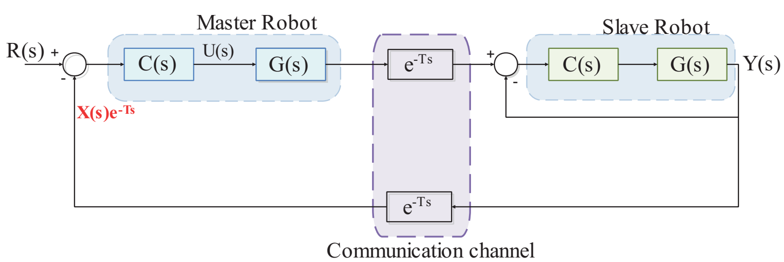


Figure 1. Teleoperation system.

In Figure 1, the feedback signal to the master is delayed, which makes the system unstable. The closed loop transfer function for the teleoperation system in Figure 1 is obtained as follows:

$$G_{closed}(s) = \frac{C^2(s)G^2(s)e^{-Ts}}{1 + C(s)G(s) + C^2(s)G^2(s)e^{-2Ts}} \tag{1}$$

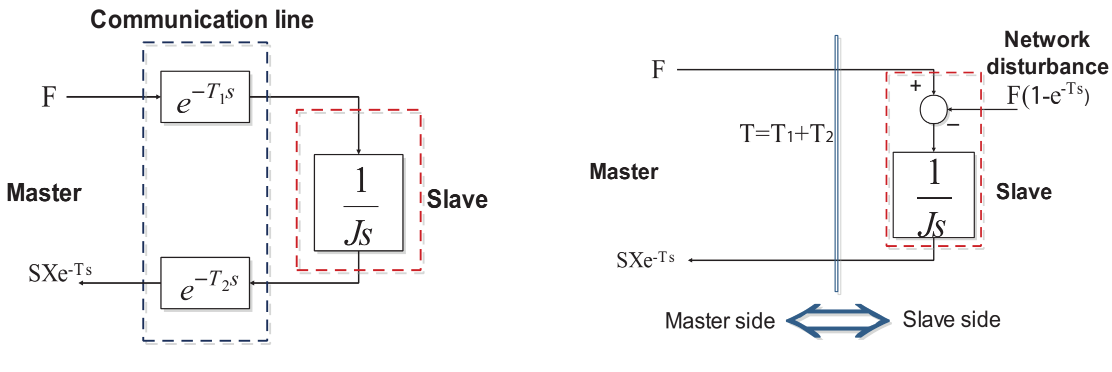
According to Eq. (1), due to the time delay element in the characteristic polynomial, the system is destabilized. Hence, applying a time delay compensation method is critical.

Consequently, many studies are dedicated to different means of time delay compensation in time-delayed systems.

3. ND concept in teleoperation systems

In [23], using the ND concept in a simple time-delayed system, it was demonstrated that a system with input delay and output delay is equivalent to a system with ND. Therefore, the effects of time delay are regarded as the effects of ND. Figure 2 shows the concept of ND in teleoperation systems [15]. In Figure 2a, J, T_1, and T_2 are the slave's inertia, time delay from the master side to the slave side, and time delay from the slave side to the master side, respectively. F is the control input for the slave (force or torque dimension) and sXe^{-Ts} is the output of the slave (angular velocity dimension). Due to time delay in the communication line, the feedback signal to the master is delayed and thus phase delay makes the system unstable. Considering the concept of ND defined as Eq. (2), Figure 2a is equivalent to Figure 2b. In Figure 2b, there exists ND instead of a time delay element.

$$D_{net}(s) = F(s) - F(s)\, e^{-Ts} \tag{2}$$



(a) (b)

Figure 2. ND concept in teleoperation system: (a) system with time delay, (b) system with ND.

4. Effect of model uncertainty and disturbance on the conventional CDOB

In this section, some defects of the conventional CDOB presented in [15,17] are analyzed. By applying the first-order CDOB to the teleoperation system in Figure 3, the estimated network disturbance is used for time delay compensation and thus the feedback signal to the master is not delayed anymore. Therefore, time delay effect is compensated by the CDOB. To obtain the closed-loop transfer function of Figure 3, it is assumed that the cutoff frequency of the CDOB is near infinite. This means that the CDOB ideally estimates ND and $|L(s)|$ is equal to 1. Thus, the closed-loop transfer function of the teleoperation system with the conventional CDOB is derived as follows:

$$G_{closed}(s) = \frac{Y(s)}{R(s)} = \frac{C^2(s)\, G^2(s)\, e^{-Ts}}{1 + C(s)\, G(s) + C(s)\, \hat{G}(s) + C^2(s)\, G(s)\, \hat{G}(s)} \tag{3}$$

Since by using the conventional CDOB the time delay element does not exist in the denominator of Eq. (3), destabilization by time delay cannot occur [23]. Therefore, the conventional CDOB makes the time-delayed system stable.

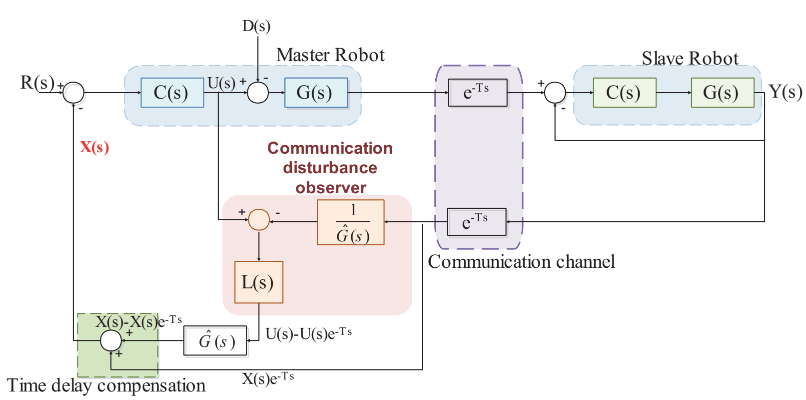


Figure 3. Time delay compensation by the conventional CDOB.

To study the robustness of the conventional CDOB, in this paper two identical 1-DOF rotary manipulators are considered as the master and the slave manipulator. The manipulator motion is described as follows:

$$Js^2 = \tau \tag{4}$$

Here J is the inertia and τ is the input torque. The controller $C(s)$, the transfer function of robots $G(s)$, and the transfer function model of robots $\hat{G}(s)$ are defined as follows:

$$C(s) = J_m(K_p + K_v s) \tag{5}$$

$$G(s) = \frac{1}{Js^2} \tag{6}$$

$$\hat{G}(s) = \frac{1}{J_m s^2} \tag{7}$$

Here J_m is the inertia model and K_v and K_p are derivative and proportional control gain of the controller, respectively. The difference between J_m and J is defined as the model error.

By substituting Eqs. (5), (6), and (7) in Eq. (3), the closed-loop transfer function is derived as below:

$$G_{closed}(s) = \frac{J_m^2(K_p + K_v s)^2 e^{-Ts}}{J^2 s^4 + J^2 J_m s^2(K_p + K_v s) + J^2 s^2(K_p + K_v s) + J J_m (K_p + K_v s)^2} \tag{8}$$

From the closed-loop transfer function, the error function is calculated and by the final value theorem the steady-state error with the unit step as command signal is obtained as follows:

$$\lim_{s \to 0} sE(s) \to 1 - \frac{J_m}{J} \tag{9}$$

From Eq. (9), it is found that steady-state error occurs when there is model uncertainty. The conventional CDOB presented in previous studies does not provide desirable performance in tracking; therefore, the need for a new structure of CDOB is undeniable.

In Figure 3, $D(s)$ is the disturbance that might be applied to the master robot unconsciously by user. The disturbance in teleoperation systems is usually an impulse function. By assuming that the cutoff frequency of CDOB is ideally infinite and $|L(s)|$ is equal to 1, the effect of disturbance on the output is described as in Eq. (10). In the case of impulse disturbance ($D(s) = 1$), the steady-state response by using Eq. (10) is obtained as in Eq. (11).

$$\frac{Y(s)}{D(s)} = \frac{-C^2(s)G^2(s)e^{-Ts}(1 + C(s)\hat{G}(s))}{1 + C(s)\hat{G}(s) + C(s)G(s) + C^2(s)G(s)\hat{G}(s)} \tag{10}$$

$$\lim_{s \to 0} sY(s) \to -\infty \tag{11}$$

This shows that the impulse disturbance causes serious steady-state error in the conventional CDOB, confirming the need for a new structure.

5. Proposed structure for CDOB in teleoperation systems

This section presents a new structure of CDOB based on [18] to achieve robust stability. In the time delay compensation method by the conventional CDOB, model uncertainty of the observer to the controlled system affects ND estimation. Model uncertainty is modeled as the disturbance, defined as follows:

$$D_{model}(s) = (J - J_m)s^2X(s) = \Delta Js^2X(s) \tag{12}$$

Since this disturbance is a kind of force, it will be estimated by the CDOB certainly.

The estimated value of CDOB ($\hat{D}_{net}(s)$) includes the effect of model uncertainty ($D_{model}(s)e^{-Ts}$) shown in Figure 4. To achieve the correct ND estimation by the CDOB, the effect of model uncertainty must be removed from the estimated ND. From Eq. (2) and Eq. (12), the value of the estimated network disturbance without the effect of model uncertainty is calculated as follows:

$$\hat{D}_{net}(s) = D_{net}(s) - D_{\bmod el}(s) = \hat{U}(s) - \hat{U}(s)e^{-Ts} \tag{13}$$

As in Eq. (13), the value of the network disturbance can be calculated from the system torque input and the delayed system torque input. By this method, the effect of model errors is eliminated.

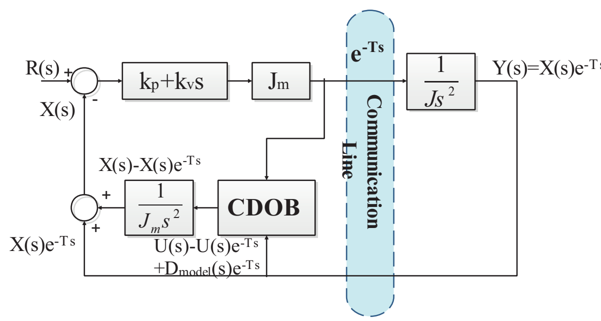


Figure 4. The effect of model uncertainty on ND estimation by the conventional CDOB.

In the conventional CDOB, inputs of the CDOB are the master torque and the delayed slave's position. However, to remove the model uncertainty effect from the estimated value of ND, inputs of the CDOB should be changed as in Eq. (13). Although in [18] for a time-delayed system the system torque input and the delayed system torque input are clear, in teleoperation systems these signals are more complex and should be determined properly. Applying the structure in [18] to teleoperation systems does not provide stability, as the master torque can be considered the system torque input, but it is not possible to consider the slave torque as the master's delayed torque. These two are not exactly identical. Hence, in this paper, by multiplying the slave's delayed position by the inverse of the transfer function of the slave robot, its delayed torque is calculated. The structure of the conventional CDOB has been changed and the network disturbance for compensation of time delay is calculated from the master torque and the slave's delayed torque instead of its delayed position. A block diagram of the proposed structure is shown in Figure 5. The closed-loop transfer function of the proposed structure is obtained as in Eq. (14) and by substituting Eqs. (5), (6), and (7) in Eq. (14), the closed-loop transfer function is derived as in Eq. (15).

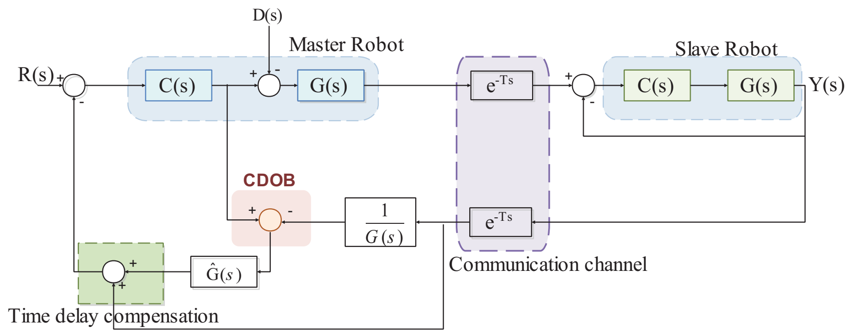


Figure 5. Proposed structure for the CDOB.

The time delay component in the denominator of the closed-loop transfer function of Eq. (14) might affect the stability of the system. The stability is analyzed using the open-loop transfer function of the proposed structure and the Nyquist criterion.

$$G_{closed}(s) = \frac{Y(s)}{R(s)} = \frac{C^2(s)G^2(s)e^{-Ts}}{1+C(s)G(s)+C(s)\hat{G}(s)+C^2(s)G(s)\hat{G}(s)+C^2(s)G^2(s)e^{-2Ts}-C^2(s)G(s)\hat{G}(s)e^{-2Ts}} \tag{14}$$

$$G_{closed}(s) = \frac{J_m^2(K_p+K_v s)^2 e^{-Ts}}{J^2s^4+JJ_ms^2(K_p+K_vs)+J^2s^2(K_p+K_vs)+JJ_ms^2(K_p+K_vs)^2+J_m^2(K_p+K_vs)^2e^{-2Ts}-JJ_ms^2(K_p+K_vs)^2e^{-2Ts}} \tag{15}$$

Figure 6 shows the Nyquist plots of several cases of time delays and model uncertainty $J_m/J = 1.2$, and Figure 7 shows the Nyquist plots of several cases of model uncertainty with time delay $T = 200\,ms$. Since there is no encirclement of –1, the system is stable in all cases of time delay and model uncertainty.

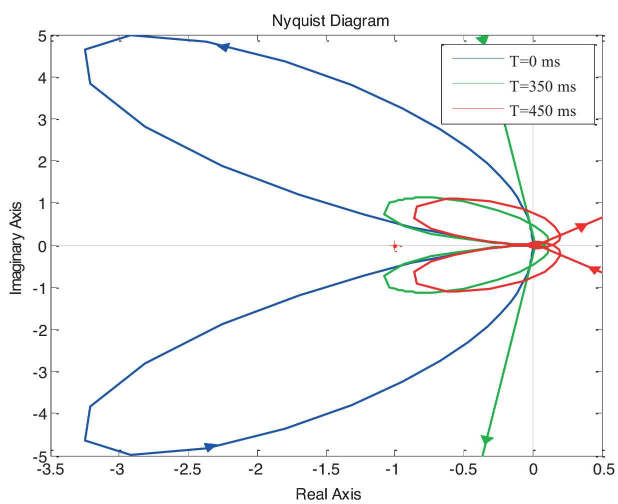


Figure 6. Nyquist plot with various time delay for proposed system with Jm/J = 1.2.

5.1. Robustness of the proposed CDOB

To show the effect of model uncertainty on the steady-state characteristic in the proposed CDOB, by using Eq. (14), the error function can be derived and by means of final value theorem the steady-state error with step unit as command signal is obtained as below:

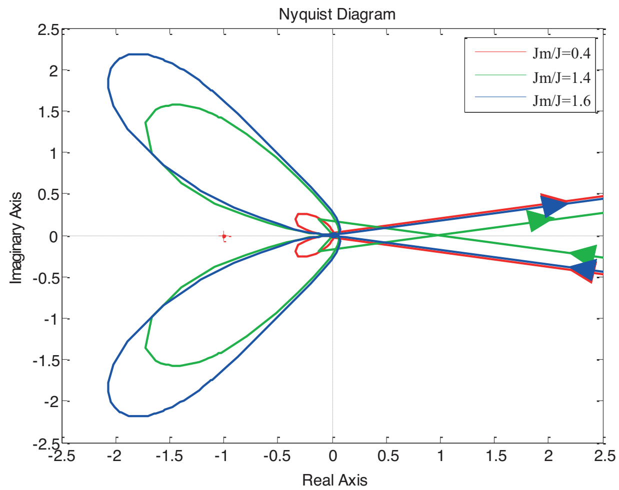


Figure 7. Nyquist plot with various model uncertainties for proposed system with T = 200 ms.

$$\lim_{s \to 0} sE(s) \to 0 \tag{16}$$

It is shown that, in teleoperation systems with the proposed CDOB, the steady-state characteristics are not affected by model uncertainty. Thus, robust stability is provided for the system.

For the proposed structure in Figure 5, the effect of disturbance $(D(s))$ applied to the master robot on the output $Y(s)$ is obtained as in Eq. (17). The effect of impulse disturbance on the steady-state response by using Eq. (17) is derived as in Eq. (18).

$$\frac{Y(s)}{D(s)} = \frac{-C(s)G^2(s)e^{-Ts}}{1 + C(s)G(s) + C(s)\hat{G}(s) + C^2(s)G(s)\hat{G}(s) + C^2(s)G^2(s)e^{-2Ts} - C^2(s)G(s)\hat{G}(s)e^{-2Ts}} \tag{17}$$

$$\lim_{s \to 0} sY(s) \to 0 \tag{18}$$

Hence, by the proposed method, even in presence of model uncertainty, there is no steady-state error when an impulse disturbance is exerted on the master. In fact, the proposed structure for the CDOB attenuates the disturbance characteristic.

6. Experiment

In this section, experimental results are presented to demonstrate the effectiveness of the proposed CDOB (Figure 5) compared with the Smith predictor and some structures of CDOBs in previous studies. All experiments are conducted under unknown and time-varying delay. Meanwhile, the position and force response are investigated. First the experimental setup is described. Then experimental results are shown and a comparison between the proposed CDOB and other structures is presented.

6.1. Experimental setup

In this experiment, the models of two identical 1-DOF rotary manipulators described in Eq. (4) are considered as the master and the slave manipulator. Using Simulink, each model with its controller is run on a separate computer as the master and the slave robots, meaning that the master and the slave robots have their own computers that are connected through the TCP/IP protocol shown in Figure 8. In past research, time-varying delay in the communication channel was simulated by PCs, but in this paper, Lab Internet is used as the communication channel. Moreover, to implement the real teleoperation system conditions, a VPN network is created between the master and the slave computers to increase the value of time delay in the communication channel. In this VPN network, the computers have their own IPs and thus the master and the slave system are able to find each other easily to send data. In this way, the average of the approximated round-trip time delay in the communication channel is raised to 300–1000 ms. Since time delay in the Internet is unknown and time-varying, the value of time delay is different in each setup. For example, two cases of pinging of the PC that contains the slave model are obtained as in Figure 9. Consequently, a real communication channel has been implemented in this paper. It should be noted that our experiments are conducted under unknown

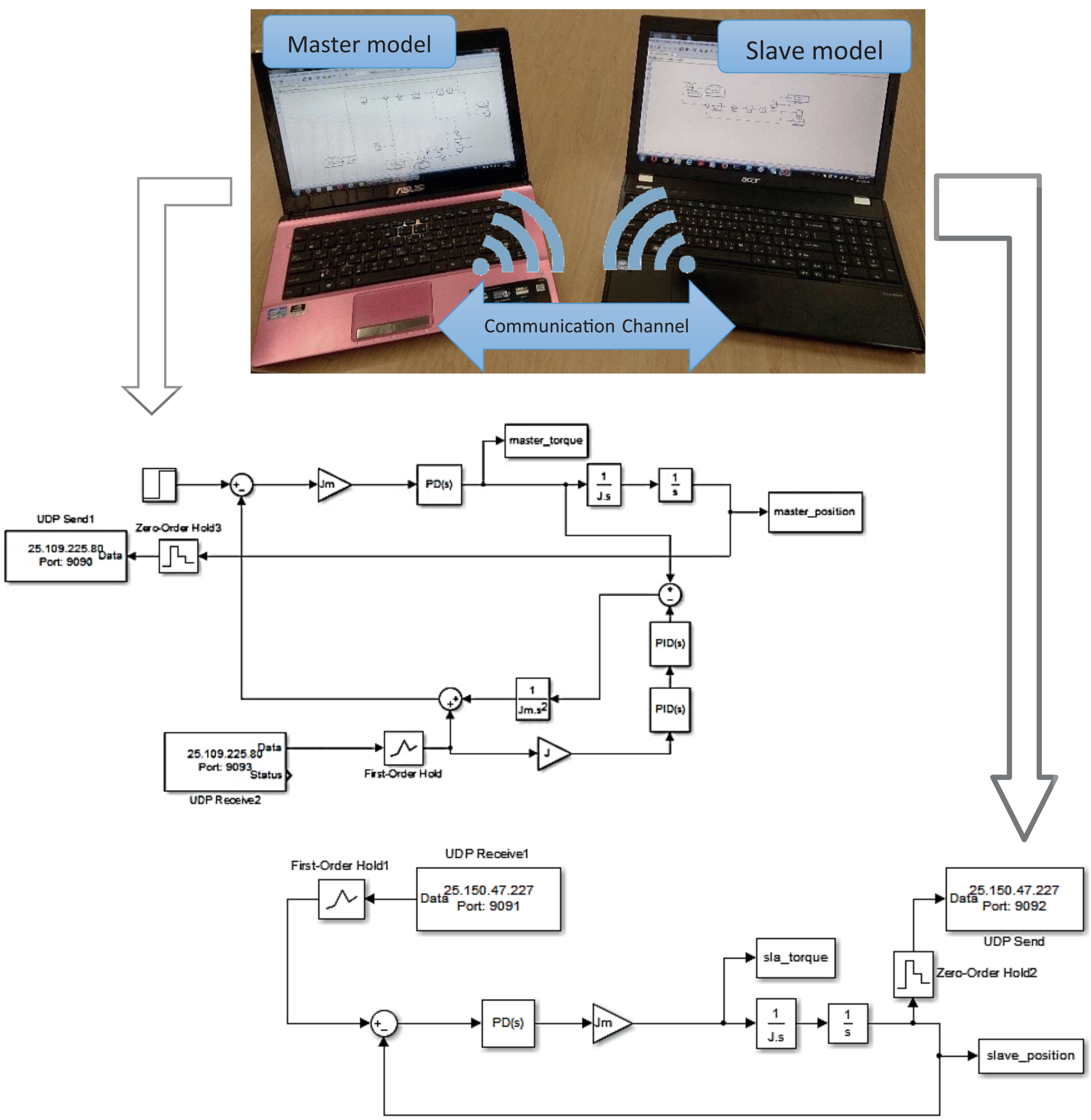


Figure 8. Implementation of communication channel in experiment setup.

and time-varying delay, meaning that we consider a real network as the communication channel, which includes any type of time delay with chattering. For example, one model of time delay in the communication channel happens as in Figure 10. Moreover, the desired position predefined by the user is a unit-step signal.

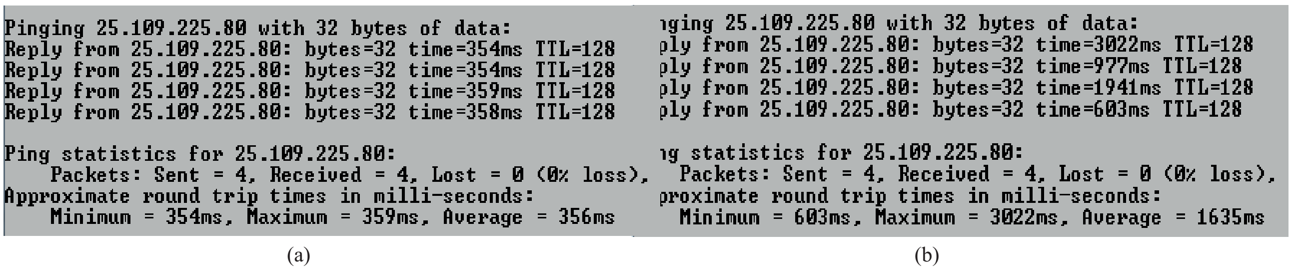


Figure 9. Different conditions of time-varying delay in experimental setup.

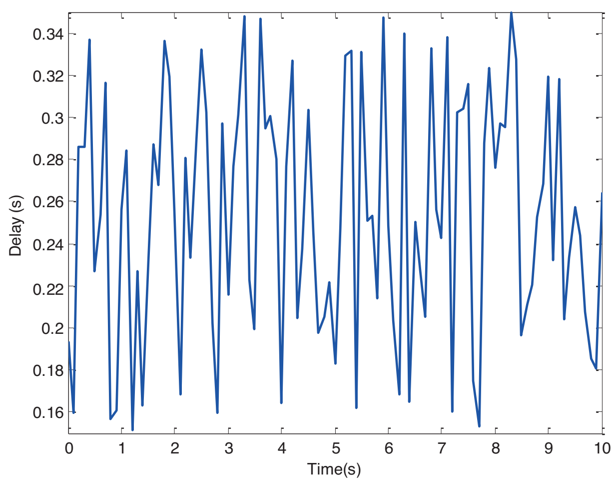


Figure 10. Time delay.

6.2. Design of control parameters

In order to achieve desirable transient characteristics, controller parameters should be designed properly. To do this, the system should be regarded as the system without time delay, meaning that time delay effect is completely compensated [24]. Then the controller parameters will be designed by pole placement method. Figures 11 and 12 show the effect of K_v and K_p on pole placement, respectively. In Figure 11, K_v is set as 10 and in Figure 12, K_p is set as 25. From Figure 11, it turns out that by increasing the proportional gain of the controller, the system tends to be unstable. The imaginary parts of the dominant poles become larger and thus the oscillations of the system will be increased. On the other hand, from Figure 12, it is found out that as K_v increases, the imaginary parts of the dominant poles decrease, so fluctuations of the system are reduced. However, by increasing K_v, the dominant poles move to the right in the complex plane, meaning that excessive derivative gain makes the system unstable. Therefore, considering these analytical results, the values of parameters used in this paper are shown in the Table.

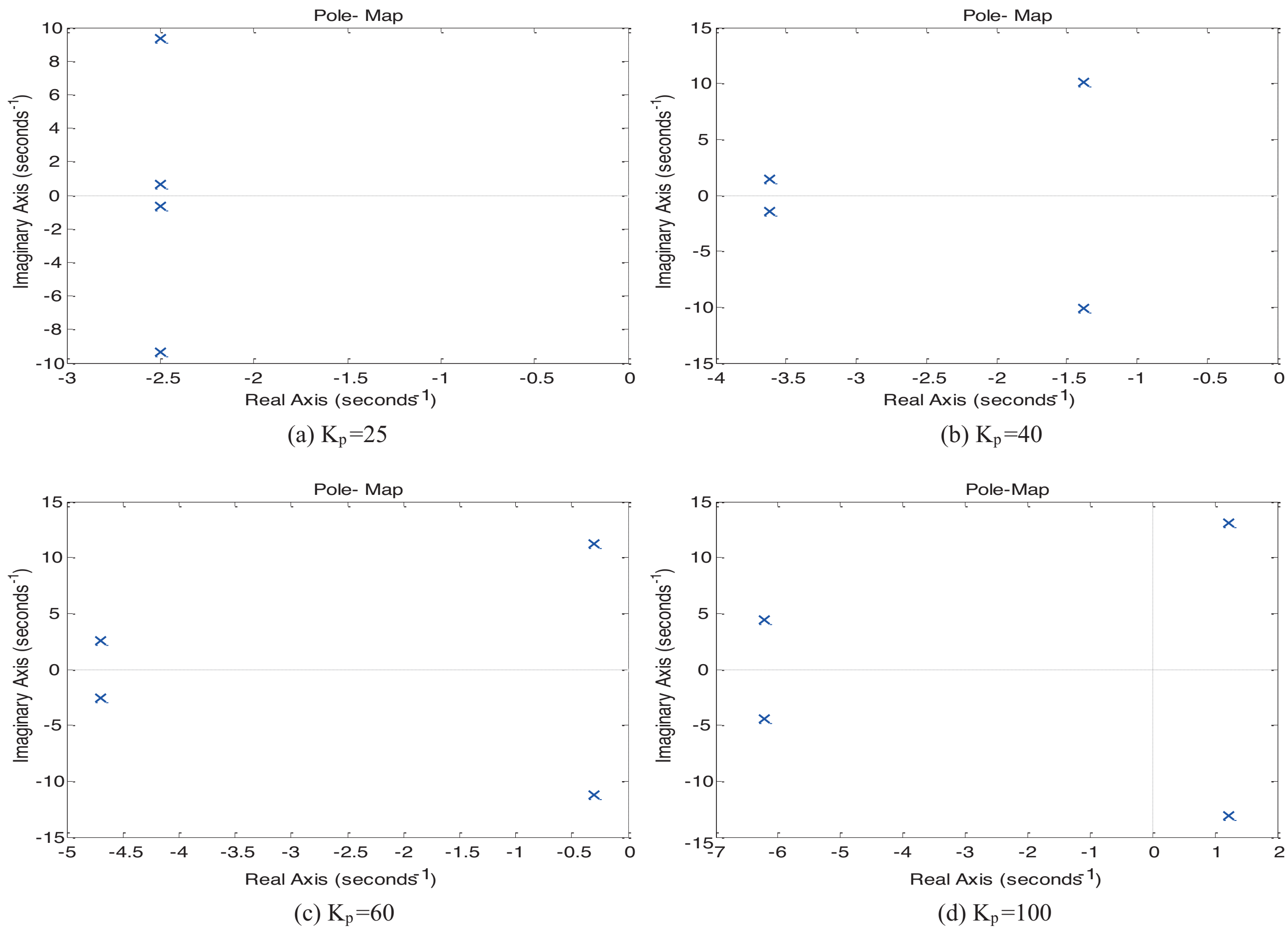


Figure 11. Effect of the proportional gain of controller on pole placement.

Table. Parameters.

Simulation parameters		
Parameter	Meaning	Value
J	Moment of inertia	0.005 kgm^2
K_p	Position gain	25
K_v	Velocity gain	20

6.3. Comparison between Smith predictor and the proposed CDOB

The effectiveness of the Smith predictor (Figure 13) in time delay compensation depends on time delay model T_m and the controlled system model. In teleoperation systems in which Internet is used as the communication channel, time delay is unpredictable and there is no exact model for time delay. Figures 14a and 14b shows the experimental results for both the Smith predictor with $T_m = 500ms$ and the proposed CDOB. It is observed that, due to error between the time delay model of the Smith predictor and the middle value of the round-trip time-varying delay, the tracking performance of the teleoperation system is not achieved and the system becomes unstable. Figure 14b shows the superiority of the proposed CDOB in time-varying delay compensation over the Smith predictor. The slave position tracks the master position and the command signal accurately.

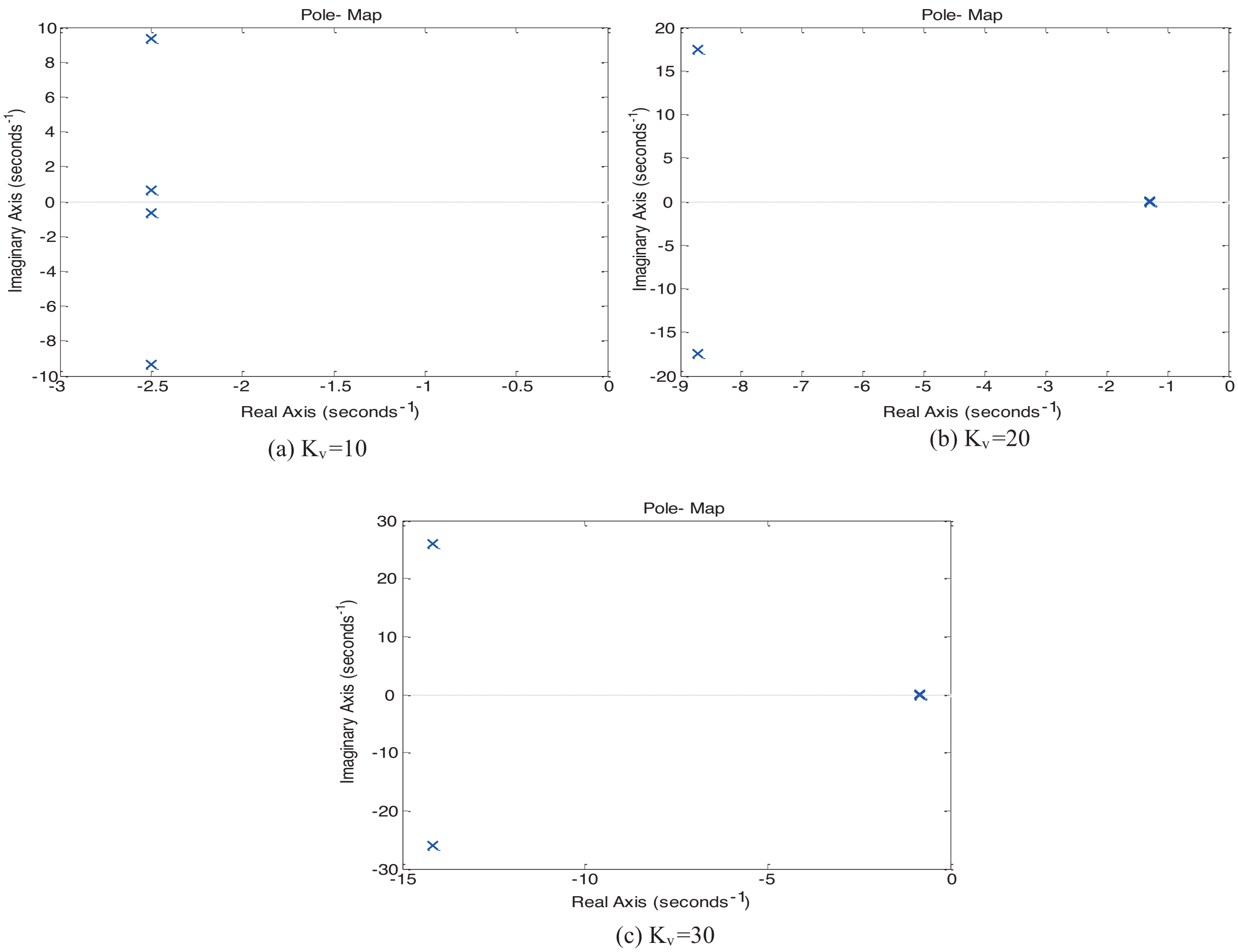


Figure 12. Effect of the derivative gain of controller on pole placement.

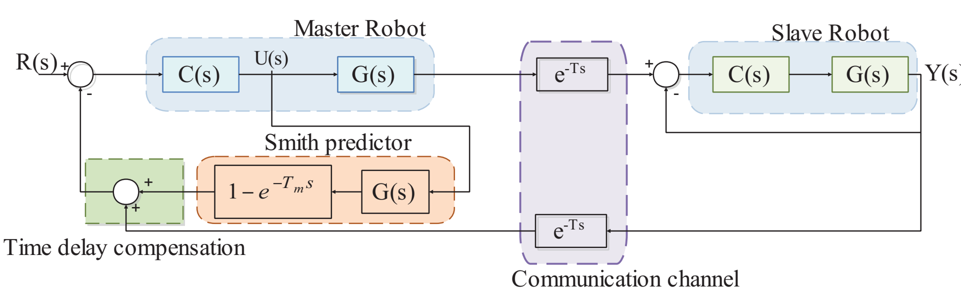
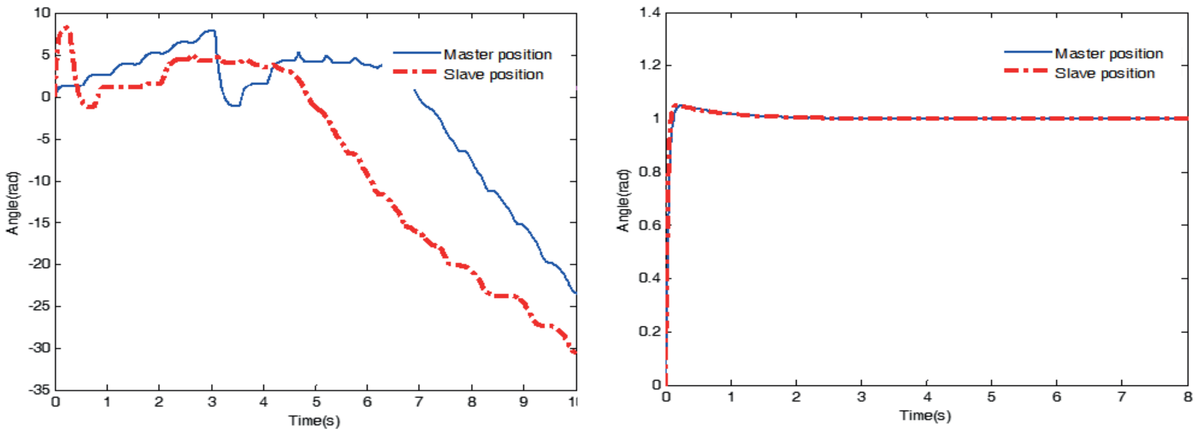


Figure 13. Time delay compensation by Smith predictor.

6.4. Comparison between the proposed CDOB and previous structures of CDOB

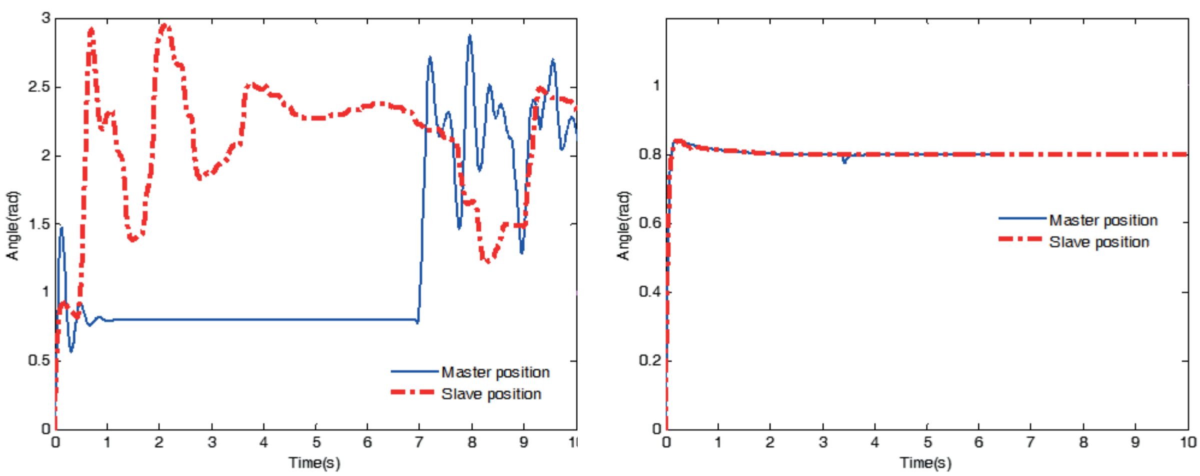
Here, experimental results to compare the proposed CDOB with the conventional CDOB and also two structures of CDOB presented in previous works are given. First, some defects of different structures of CDOB are shown. Then the advantages of the proposed CDOB are illustrated. In the conventional CDOB, to guarantee the stability of the system, the cutoff frequency of the LPF should be a large value. Figure 15 shows the



(a) (b)

Figure 14. Position response (time-varying delay): (a) Smith predictor, (b) the proposed CDOB.

experimental results for the conventional CDOB with two different values of cutoff frequency. In Figure 15a the design condition of the first-order CDOB presented in [23] is not satisfied; thus, ND estimation for time delay compensation is not accomplished well and the system becomes unstable. On the other hand, in Figure 15b, by setting a large value for the cutoff frequency, the LPF of the conventional CDOB satisfies the design condition and thus stability of the system is provided. According to these results, it is found that in the conventional CDOB the stability of the system depends on the value of the cutoff frequency of the LPF and to stabilize the system this value should be designed as a large value. However, due to some limitations of devices, this is not possible in all situations and so this dependency is not desired.



(a) (b)

Figure 15. Position response for teleoperation system with the conventional CDOB with model uncertainty Jm/J = 0.8: (a) gnet = 20, (b) gnet = 300.

In Figure 15, the conventional CDOB is stable with a large value of cutoff frequency, but model uncertainty causes steady-state error between position response and command signal. Robust stability is not achieved.

To reduce the steady-state error due to model errors in time-delayed systems with CDOBs, a simple approach was presented in [21]. In this method, system models are designed as different values. By applying this method to teleoperation systems (Figure 16), the closed-loop transfer function of the system is described as in Eq. (19).

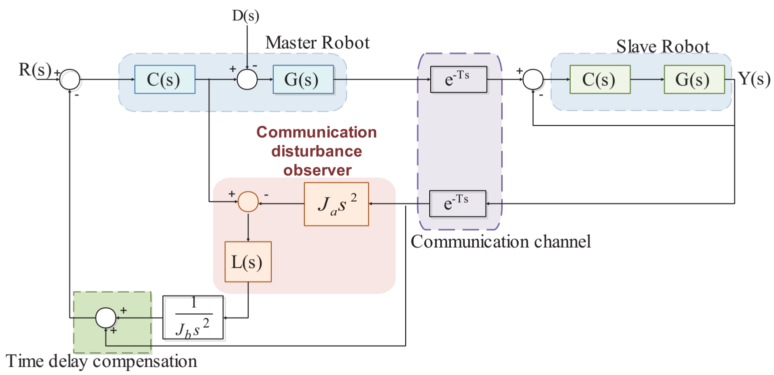


Figure 16. Teleoperation system with reduction method presented in [20].

$$G_{closed}(s) = \frac{J_m^2(K_p+K_v s)^2 \frac{1}{J^2 s^4} e^{-Ts}}{1+J_m(K_p+K_v s)\frac{1}{Js^2}+J_m(K_p+K_v s)\frac{1}{J_b s^2}+J_m^2(K_p+K_v s)^2\frac{1}{JJ_b s^4}+J_m^2(K_p+K_v s)^2\frac{1}{J^2 s^4}e^{-2Ts}-J_m^2(K_p+K_v s)^2\frac{1}{J^2 s^4}\frac{J_a}{J_b}} \quad (19)$$

It is assumed that the cutoff frequency is infinite. The steady-state error in the case of unit step, by means of the final value theorem, is obtained as in Eq. (20). As in Eq. (20), by increasing the difference between J_a and J_b, the steady-state error can be decreased. J_a and J_b should be designed properly to reduce the steady-state error.

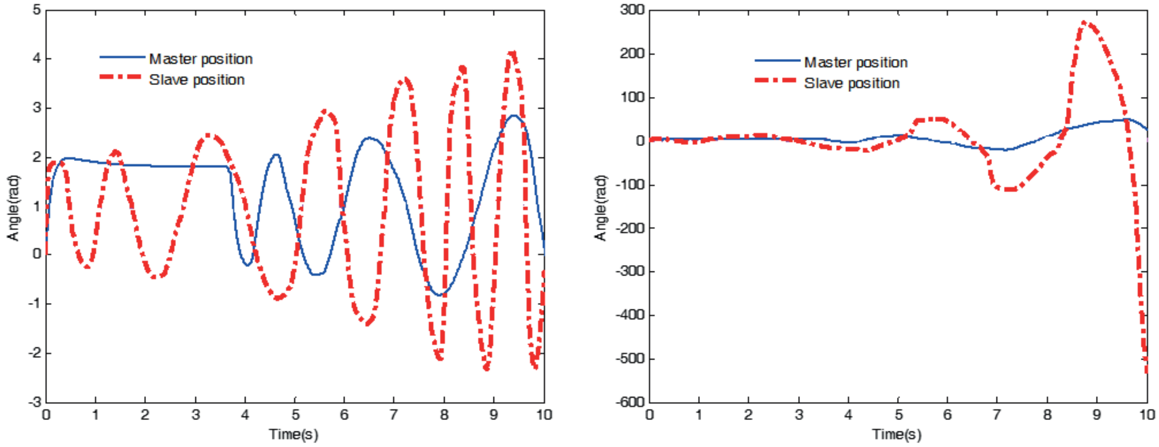
$$\lim_{s \to 0} sE(s) = \frac{J - J_a}{J + J_b - J_a} \quad (20)$$

However, from Eq. (20) it turns out that the time delay element in the denominator might affect the stability of the system. Therefore, J_a and J_b should be designed considering the stability.

Figure 17 shows the experimental results of applying the reduction method of steady-state error presented in [21] to teleoperation systems. J_a is assumed to be the same as J_m (in the controller), so J_b should be designed to reduce the steady-state error. By setting model uncertainty as $J_m/J = 0.8$, two values of J_b are analyzed. It is observed that the performance of the system deteriorates; thus, this method is not efficient for large time-varying delay. The stability of this structure with different time delays is analyzed using the Nyquist criterion in Figure 18. Since there is encirclement of -1, the system is unstable and the reduction method of the steady-state error in [21] is not efficient for teleoperation systems under large time delays.

On the other hand, the experimental results to verify the robustness of teleoperation systems with the proposed CDOB against model uncertainty are presented in Figure 19. It turns out that since the CDOB does not need the time delay model, it compensates the effect of time-varying delay and the system remains stable. Moreover, compared with the conventional CDOB in Figure 15b, the model uncertainty does not affect steady-state characteristics and the steady-state error is completely eliminated. The slave's position tracks the master's position and command signal accurately.

Figures 20 and 21 shown the experimental results of the disturbance attenuation characteristic of the conventional CDOB and the proposed CDOB, respectively. An impulse disturbance is exerted on the master



(a) (b)

Figure 17. Position response for teleoperation system with reduction method in [20] by Jm/J = 0.8: (a) Jb = 1.8 J, (b) Jb = 2.8 J.

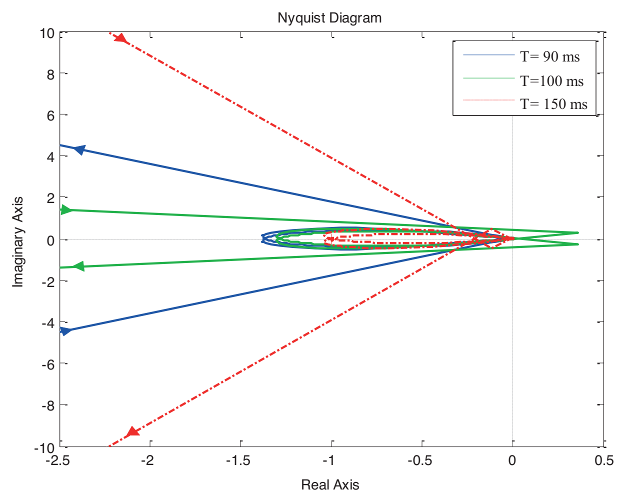
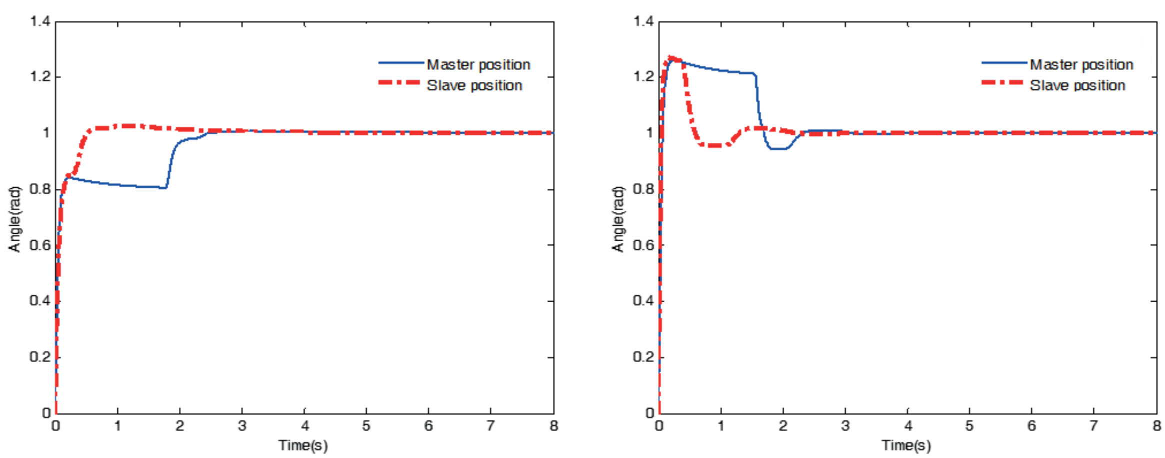


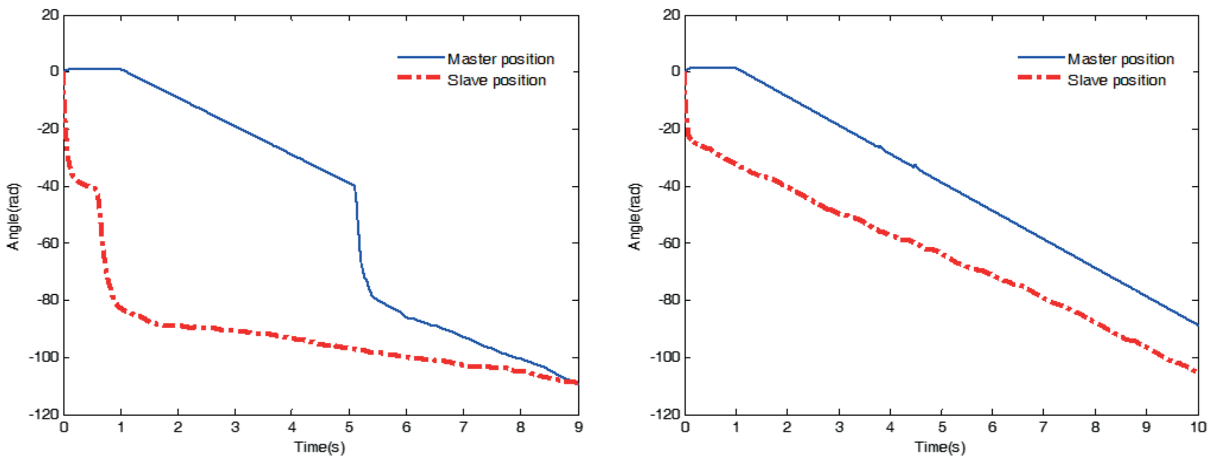
Figure 18. Effect of different values of time delay on stability (Jb = 1.8 J).



(a) (b)

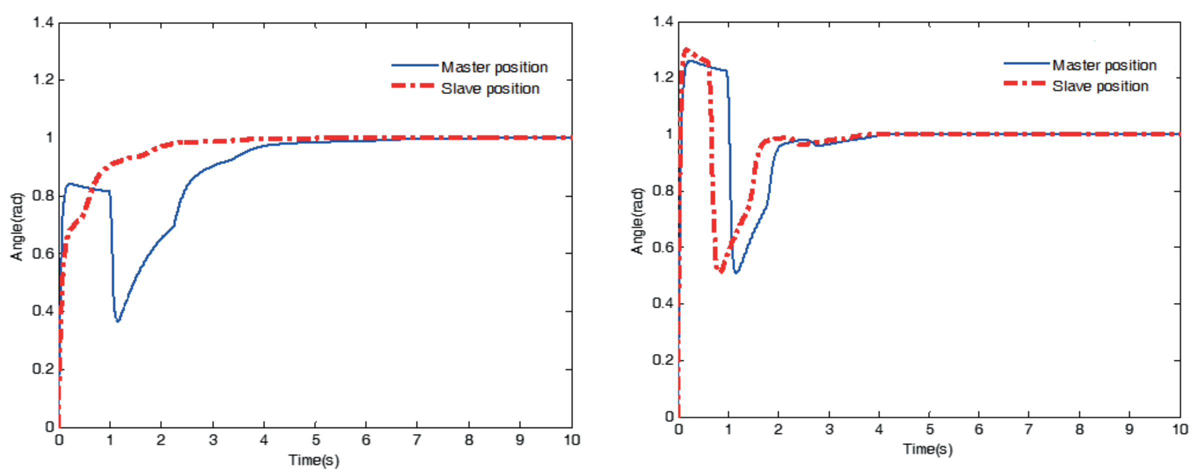
Figure 19. Position response for system with the proposed CDOB: (a) Jm/J = 0.8, (b) Jm/J = 1.2.

robot at t = 1 s. From Figure 20, it turns out that in teleoperation systems with the conventional CDOB, impulse disturbance causes serious steady-state error and the tracking performance from the command signal is not accomplished. Using the proposed structure of CDOB in Figure 21, it is clarified that there is no steady-state error due to impulse disturbance, which is an advantage of the proposed structure. For example, in a teleoperation system like telesurgery, unexpected impulses from surgeon to master robot should not stop the slave position from tracking the master position.



(a) (b)

Figure 20. Effect of an impulse disturbance on conventional CDOB: (a) Jm/J = 0.8, (b) Jm/J = 1.2.



(a) (b)

Figure 21. Effect of an impulse disturbance on proposed CDOB: (a) Jm/J = 0.8, (b) Jm/J = 1.2.

By increasing the proportional gain of the controller, it is possible to decrease the settling time of the response, as shown in Figure 22. The system response becomes faster. However, the overshoot is increased slightly. In these results, the value of the proportional gain is selected as $K_p = 100$.

6.5. Discussion and comparison

Experimental results show the merits of the proposed CDOB in comparison to some time delay compensation methods. The performance of the Smith predictor deteriorates due to time-delay model errors so it is not effective in time-varying delay compensation, while the CDOB does not need a time delay model. Therefore, the CDOB can be implemented in cases of unknown distribution of time-varying delay like IP networks. On the other hand, the stability of the conventional CDOB depends on the value of the cutoff frequency. Moreover, in the conventional CDOB and two other structures of CDOBs presented in previous works, model uncertainty of the controlled system affects the steady-state characteristic, but the proposed CDOB is robust against model uncertainty and the external disturbance on the master robot. In other words, the proposed CDOB is independent of cutoff frequency and also eliminates the steady-state error completely.

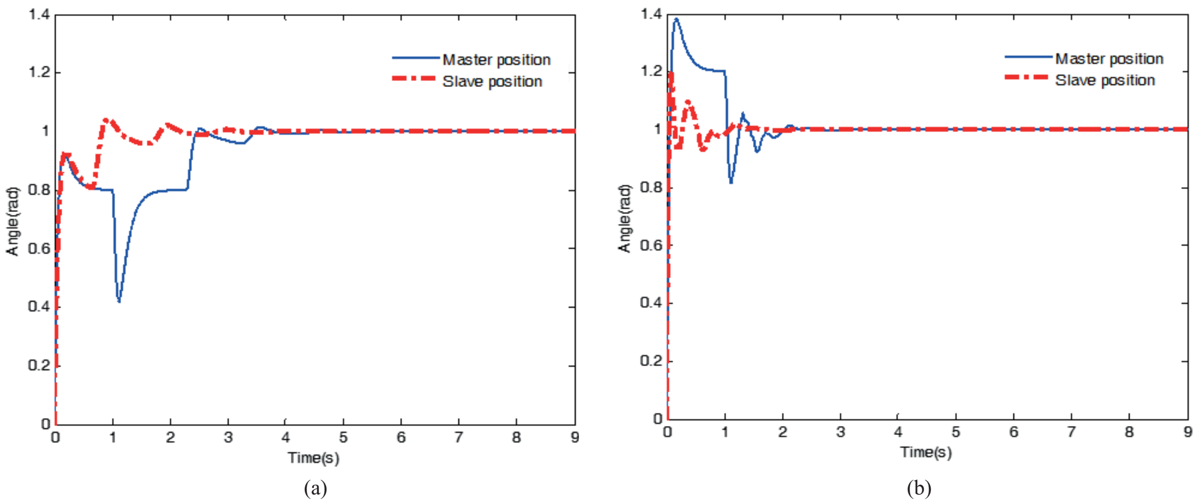


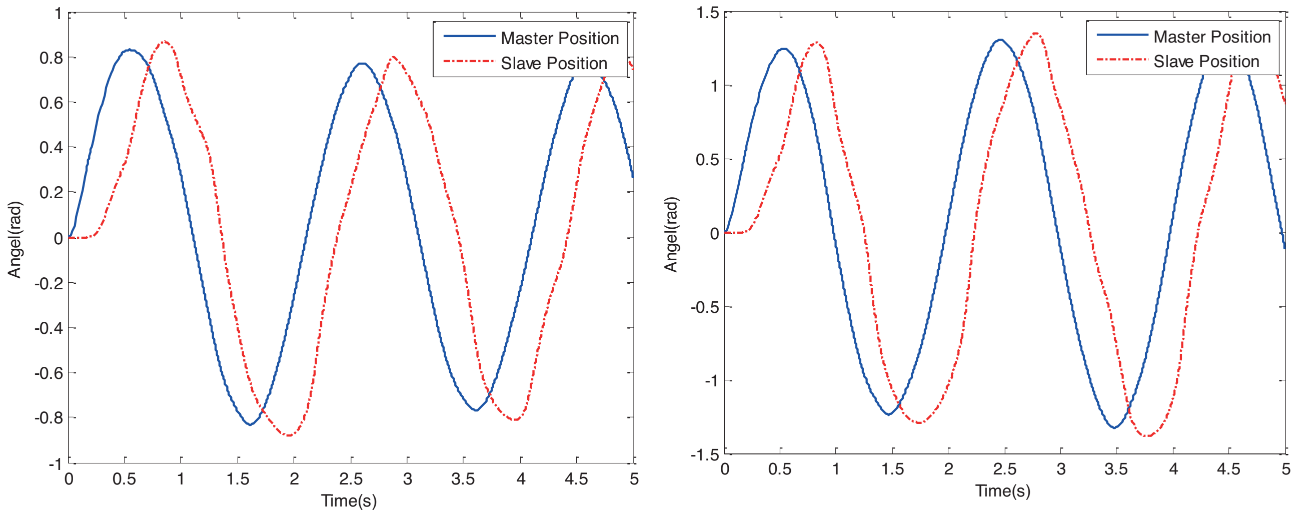
Figure 22. Effect of an impulse disturbance on the position response of the proposed CDOB by Kp = 100: (a) Jm/J = 0.8, (b) Jm/J = 1.2.

7. Sinusoidal input

In the case of sinusoidal reference, the results for slave position and master position are represented in Figures 23. It is found that the system is stable in the presence of variable time delay and also model uncertainty. Moreover, the slave position tracks the master position properly and there is no steady-state error in the presence of model uncertainty.

8. Conclusion

In this paper, a new structure of a CDOB for teleoperation systems has been presented to achieve robust stability. In the conventional CDOB, inaccurate network disturbance estimation due to model uncertainty of the observer and the controlled system has led to steady-state error. Thus, according to the novel structure in [18] for time-delayed systems, another structure for a CDOB in teleoperation systems is proposed that uses the slave's delayed torque instead of its delayed position. This proposed structure provides zero steady-state error even in the presence of model uncertainty and impulse disturbance. By designing the value of controller parameters, desirable transient response is achieved. For validation of the proposed structure of the CDOB, the communication channel is implemented through a TCP/IP protocol in the experimental setup. Therefore, the validity of the proposed structure is verified in real time-varying delay conditions. The experimental results demonstrate the superiority of the proposed structure over the conventional CDOB, the Smith predictor, and some other structures of CDOBs.



(a) (b)

Figure 23. Position response for system with the proposed CDOB in the case of sinusoidal input: (a) Jm/J = 0.8. (b) Jm/J = 1.2.

In future work, we will study different models for the robots and the controllers in master and slave sides in the presence of time delay.

Nomenclature

D_{net}	Network disturbance
J	Inertia
τ	Torque
$\hat{U}(s)$	Estimated torque

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