Bilateral Control to Achieve Transparent Teleoperation with Perturbation of Static Time Delay

Alireza Alfi
Faculty of Electrical engineering
Iran University of Science and Technology
Tehran 16846-13114
Iran
a_alfi@iust.ac.ir

Mohammad Farrokhi
Faculty of Electrical Engineering
Iran University of Science and Technology
Tehran 16846-13114
Iran
farrokhi@iust.ac.ir

***Abstract* – This paper presents a novel structure design for bilateral teleoperation control systems with some perturbations in time delay in communication channel. Transparency is used as an index to evaluate the performance of the teleoperation system. The focus of this paper is to achieve transparency for bilateral teleoperation system in presence of variations in time delay in communication channels as well as stability. To achieve transparency in the proposed structure, two controllers are used for bilateral teleoperation. The controllers force the slave manipulator to follow the master in spite of small variable time delays in communication channel. An adaptive FIR filter estimates the time delay. Furthermore, the stability of the closed-loop system despite estimator error in adaptive filter will be proved. The advantages of the proposed method are simple design and flexibility of the control method. Simulation results show very good and promising results despite small and varying time delay. Moreover, the proposed method provides a technique for predicting the time delay in order to avoid system instability.**

I. INTRODUCTION

Teleoperation systems have been used over the past two decades to perform dangerous tasks, such as mining or handling hazardous materials, or carry out jobs, which are inaccessible to operators, like space operations or remote surgeries [1]. In bilateral teleoperation system, the remote environment gives some necessary information through the feedback loop to the local site. A teleoperation system is said to be bilateral if the information signal flows in both directions between master and slave. The communication channel is the most important part in these systems. With the recent advances in communication networks, internet has been used as communication channel to transmit information from local site to remote site. But, the main drawback of Internet-based teleoperation is the variable time delay. This time delay is always present when information is exchanged from local site to remote site and vice versa. It can destabilize the bilateral teleoperation system, especially when time delay exists between local site and remote site [2]. Various methods have been proposed in literatures for handling the problem of time delay. Anderson and Spong [3] proposed new communication architecture based on the scattering theory. Niemeyer and Slotine [4] introduced the use of wave variable in teleoperation system extended from scattering theory proposed by Anderson and Spong. Impedance matching was discussed by Hogan in [5] and the robust impedance matching based on a desired impedance model and the sliding mode controller was presented by Cho and Park in [6]. Brady and Tarn [7] described the time-varying nature of the delay and developed a time-forward observed for supervisory control over the internet. Munir and Book [8] have used a Kalman filter and a time-forward observer to predict the wave variables and to compensate for the delays. In 2000, Sano et al. designed an H_∞ controller to stabilize the teleoperation system for time delay [9]. Zhu and Salcudean have used adaptive motion/force controller for unilateral or bilateral teleoperation systems [10]. Some control structures have been proposed to deal with these problems by Hastrudi-Zaad and Salcudean [11], Garcia and et al [12], Sirouspour and Shahdi [13] and Li and et al [14].
In all method, besides stability, transparency is the major criterion for performance of teleoperation systems in presence of time delay in communication channel. If the slave accurately reproduces the master's commands and the master correctly feels the slave forces, the human operator experiences the same interaction as the slave would. This is called complete transparency in teleoperation systems [15].
In this paper, a novel control method of bilateral teleoperation systems with small variable time delay in communication channel and complete transparency is proposed. In this structure, to achieve transparency, force measurement is used at the slave site, and force feedback (i.e. direct force-measurement force-reflecting control method) has been used at the master site.

The rest of this paper is organized as follows. Section 2 briefly describes general definitions of teleoperation systems. In section 3 and 4, the proposed control method in this paper is discussed. In section 5, estimation of time delay in communication channel is described. Section 6 analyses the stability of the proposed structure. Section 7 shows the simulation results. And finally, section 8 draws conclusions and gives some suggestions for the future work.

II. GENERAL DEFINITIONS

Fig. 1 depicts the general description of two-channel bilateral teleoperation, where the models of the master and the slave are combined into one block, denoted as a two-port teleoperator. In this structure, the human operator in the local environment directly drives the master, whereas the slave is located in the remote environment, ready to follow commands that human operator orders by moving the master.

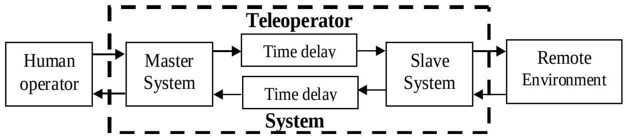

Fig. 1. The two-port teleoperator model

From the mathematical point of view, a teleoperated system is just a relationship between the position/velocity and the forces of the master and slave, i.e. a set of four signals, namely $\dot{x}_m$ (velocity of the master), $\dot{x}_s$ (velocity of the slave), f_h (human force applied on the master) and f_e (force exerted on the environment by the slave). Hence, each port of the teleoperator exchanges information about velocity and force. These signals relate to each other in terms of different two–port representations such as impedance matrix, admittance matrix, and hybrid matrix. The most important matrix for the analysis of teleoperation systems is the hybrid matrix. The hybrid matrix for the teleoperation system and its parameters are as follows [16]:

$$\begin{bmatrix} F_h(s) \\ -V_s(s) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} V_m(s) \\ F_e(s) \end{bmatrix}, \qquad (1)$$

$$h_{11} = \left.\frac{F_h}{V_m}\right|_{F_e=0} \qquad h_{12} = \left.\frac{F_h}{F_e}\right|_{V_m=0}$$

$$h_{21} = \left.\frac{V_s}{V_m}\right|_{F_e=0} \qquad h_{22} = \left.\frac{V_s}{F_e}\right|_{V_m=0}, \qquad (2)$$

where $F_h(s)$, $F_e(s)$, $V_m(s)$ and $V_s(s)$ are the Laplace transforms of $f_h(t)$, $f_e(t)$, $\dot{x}_m(t)$ and $\dot{x}_s(t)$, respectively. h_{11} is the impedance of the master, h_{12} is force scale from slave to master (force ratio), h_{21} is the velocity scale from master to slave (velocity ratio) and h_{22} is the inverse of the slave impedance. Teleoperator systems are compared by their hybrid matrix. If the operator feels as if the task environments were being handled directly, one would say "the teleoperation system is ideal" or "the master-slave pair is transparent to human-task interface". Assume that the scaling factors, the position/velocity command to the slave and the force command to the master, is unity. Then for ideal one-degree-of-freedom teleoperation system, the **H** matrix is

$$\mathbf{H}_{\text{ideal}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \qquad (3)$$

III. THE PROPOSED CONTROL SCHEME

The proposed control scheme for teleoperation systems, in presence of varying time delay in communication channels and uncertainty in task environment, has been shown in Fig. 2. In this Figure, G and C denote the transfer function of the controller; subscript m and s denote the master and slave, respectively; T_{ms} and T_{sm} denote the forward time delay (master to slave) and backward time delay (slave to master) in communication channel, respectively; F_e is the force exerted on the slave by its environment; F_h is the force applied at the master by the human operator, and F_r is the force reflected. In the proposed method, contact forces are used at the slave site. Furthermore, direct-force measurement-force reflecting control has been used at the master site. Direct-force measurement-force reflecting control is one simple form of a force reflecting scheme using a force sensor, as the contact forces are reflected to the human operator. The main goal of this control scheme is to achieve transparency and stability. This has been done by designing two local controllers; one in remote site (slave robot) C_s and the other one in local site (master robot) C_m. The remote controller guarantees the position/velocity tracking. That is, the position/velocity of the slave has to follow the position/velocity of the master. Furthermore, the local controller guarantees the stability of the overall system. Here we assume that scaling factors are equal to one and F_e is measurable. In the next sections, the design of local controllers will be described.

IV. DESIGN OF CONTROL SCHEME

A. Local Slave Controller

In this section, we propose the local slave controller. If it is assumed that the output of master and slave robot is velocity. Then, from Fig. 2, the transfer function from the slave to the master can be written as

$$\frac{V_s}{V_m} = \frac{C_s(s)G_s(s)}{1+Z_eG_s(s)+C_s(s)G_s(s)} e^{-sT_{ms}}, \qquad (4)$$

Since the forward time delay doesn't appear in the denominator of the above equation, time delay will not affect the stability. Also, we can use the classical control methods to design a local slave controller C_s for the remote site such that system in (4) is stable. So, the velocity of the slave robot will follow the velocity of the master robot in such a way that the tracking error for velocity is satisfactory.

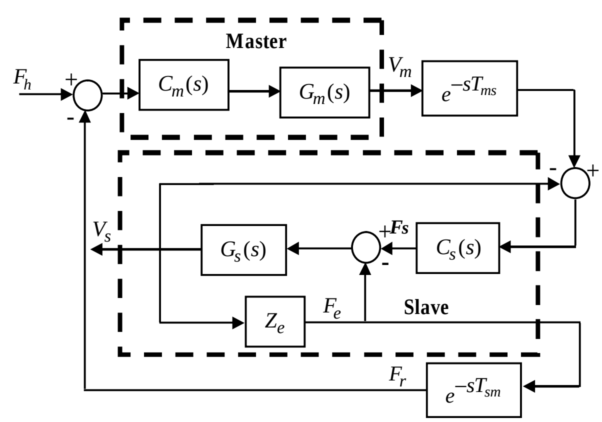

Fig. 2. The proposed control scheme (the first form)

B. Local Master Controller

Based on direct force-measurement force-reflecting control, we propose the local master controller, which can assure the stability of the closed-loop system as well as the force tracking problem. The force tracking means the reflecting force has to follow the human operator force. Now, let define the following variables:

$$\hat{G}_s(s) = \frac{Z_e C_s(s) G_s(s)}{1 + Z_e G_s(s) + C_s(s) G_s(s)}, \tag{5}$$

$$G(s) = \hat{G}_s(s) G_m(s), \tag{6}$$

$$T = T_{\mathrm{ms}} + T_{\mathrm{sm}}, \tag{7}$$

$$F_r(s) = F_e(s) e^{-sT}, \tag{8}$$

Using these variables, the control scheme, shown in Fig. 2, can be simplified as Fig. 3. We notice that the local slave controller C_s is designed such that the velocity tracking is satisfied (i.e., the poles of $\hat{G}_s$ are in the left-hand side of the *S*-Plane.) Considering the force tracking, the contact force has to follow the human operator force. Since force tracking is performed by sending force contact through the reflection path of the communication channel, we may define a new output in Fig. 3. Let's define this new output as F_r. So, the system shown in Fig. 3 can be represented as the system in Fig. 4. From Fig. 4, the transfer function of the overall closed-loop system can be written as

$$M(s) = \frac{C_m(s) G(s) e^{-Ts}}{1 + C_m(s) G(s) e^{-Ts}}, \tag{9}$$

Notice that the roles of *M*(s) are the stability of the overall system and force tracking. From (9), it can be seen that delay has been contained in the denominator of the closed-loop transfer function and hence, it can destabilize the system by reducing system stability margin and degrading system performance. A fundamental problem in these systems is to handle the time delay properly, since time delay significantly deteriorates the performance of the whole system. The Smith predictor is an effective method to solve this problem [17].

This predictor can effectively cancel out time delays from the denominator in the transfer function of the closed-loop system. Fig. 5 shows the general structure of a Smith predictor.

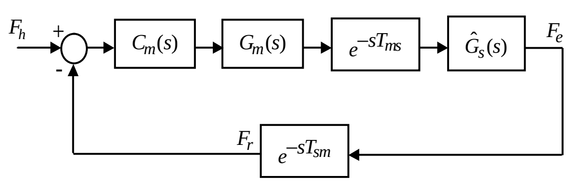

Fig. 3. New control scheme (the second form)

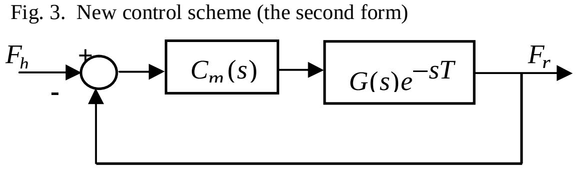

Fig. 4. New control scheme (the third form)

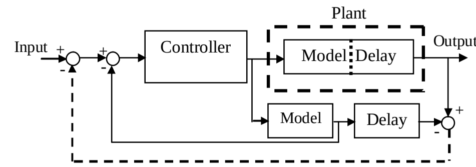

Fig. 5. The smith predictor control scheme

In other words, using the Smith predictor7, the system output is simply the delayed value of the delay-free portion of the system. So, we can use the classical control methods for designing local master controller.

The main drawback of the Smith predictor is that the time delay must be constant [18]. As it is well known, the time delay in communication channel is not constant.

In this paper, we use an identifying algorithm to estimate the time delay in communication channel, so that proper inputs can be generated for local master controller. According to Fig. 6, the closed-loop transfer function is

$$\mathrm{M}(s) = \frac{C_m(s) G(s) e^{-sT}}{1 + C_m(s) G(s) + C_m(s) G(s)[e^{-sT} - e^{-s\tilde{T}}]}, \tag{10}$$

V. ESTIMATION OF TIME DELAY

In teleoperation systems, a time delay can be defined as the time interval between the start of an event in the local site and its resulting action at the remote site. In order to estimate the varying delay time in communication channel, an adaptive FIR filter has been used. This estimator acts as an adaptive filter by minimizing the mean squared error. In other words, the filter gives an approximation of $y \in \Re$ in response to input vector $\mathbf{x} \in \Re^n$ as $y = \mathbf{w}^t \mathbf{x}$, where $\mathbf{w} \in \Re^n$ is the weight vector. Fig. 7 shows this FIR filter. The weight vector is updated according to the Least-Mean-Square (LMS) algorithm as

$$\mathbf{w}(k+1) = \mathbf{w}(k) + \gamma e(k) \mathbf{x}(k)$$

where e is the error between the estimated signal and the desired signal, and γ is called the learning rate.

Now, let the input signal be defined as

$$\mathbf{x}(k) = \left[x(kT_s) \quad x((k-1)T_s) \quad \ldots \quad x(kT_s - 2p) \right]^t, \tag{11}$$

where $x(k)$ is the sampled signal at time kT_s, T_s is the sampling time and the superscript t indicates the transpose operator. Therefore, the output signal of the filter can be calculated as

$$y(k) = \mathbf{w}^t(k) \mathbf{x}(k), \tag{12}$$

In order to estimate the time delay, we have employed the algorithm in [19], in which the time delay is modelled as an FIR filter. Assuming $T = T_{ms} + T_{sm}$ be the delay time between the forward signal $g(t)$ and the returned signal $g(t-T)$ in teleoperation system, consider the following functions:

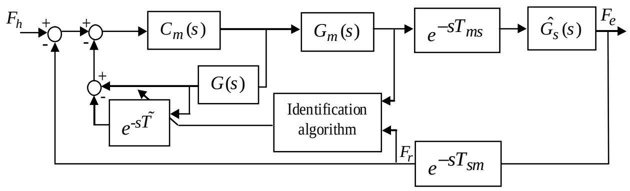

Fig. 6. Structure of local master controller

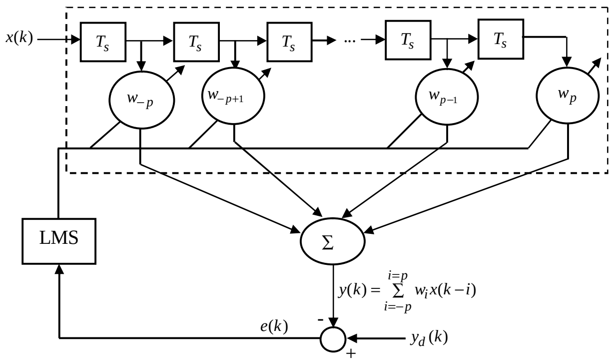

Fig. 7. Adaptive time delay estimation

$$y(t) = g(t-T) + j(t), \tag{13}$$

$$x(t) = g(t) + \Phi(t), \tag{14}$$

where $j(t)$ and $\Phi(t)$ are white and independent signal. Without loosing the generality of the problem, let the signal spectrum be bounded to $[-p, p]$ with power s^2. Then, the output of the filter is [20]

$$\hat{y}(k) = \sum_{i=-p}^{i=p} w_i x(k-i), \tag{15}$$

and the weights can be calculated as

$$\mathbf{w} = [\mathrm{sinc}(d-p) \quad \mathrm{sinc}(d-p+1) \quad \cdots \quad \mathrm{sinc}(d+p)]^t, \tag{16}$$

where

$$d = \frac{T}{T_s} \quad , \quad \mathrm{sinc}(x) = \frac{\sin(px)}{px}, \tag{17}$$

Satisfying equation (16) by weights **w**, results in quick adaptation and considerable reduction in computations. The limited summation in (15) has realized the filter on one hand and on the other hand creates nonzero error by including $j(t)$ and $\Phi(t)$ noises in $x(t)$ and $y(t)$ signals, respectively. Although, choosing $P \geq 6$ makes the estimation error in time delay insignificant [21]; but according to Equation (10), the smallest estimation error in time delay in communication channel can destabilize the teleoperation system for the proposed method. In section 6 of this paper, we will provide conditions for stability of the closed-loop system.

VI. STABILITY ANALYSIS

Suppose, there exist estimation error and let the estimated time delay be shown as $\tilde{T} = T + d$. The controller will be designed based on this time delay. The closed-loop transfer function can be written as

$$M_d(s) = \frac{C_m(s)G(s)e^{-sT}}{1 + C_m(s)G(s) + C_m(s)G(s)e^{-sT}(1-e^{-sd})} \tag{18}$$

It is obvious that the stability of the closed-loop system depends on the time delay. This fact can be shown by considering the characteristic equation of the closed-loop system

$$\Delta_d(s) = 1 + C_m(s)G(s) + C_m(s)G(s)(e^{-sT} - e^{-s\tilde{T}})$$

Now, the problem is to find d such that the closed-loop system is stable. In other words, the roots of the above characteristic equation lie in the left hand side of the S plane. To do this, let show the no delayed $G(s)$ and $C_m(s)$ as follows:

$$G(s) = \frac{N_g(s)}{D_g(s)} \quad , \quad C_m(s) = \frac{N_c(s)}{D_c(s)}, \tag{19}$$

Then, the transfer function can be rewritten as

$$M_d(s) = \frac{N(s)e^{-sT}}{D(s) + N(s)e^{-sT}(1-e^{-sd})}, \tag{20}$$

where polynomials $D(s)$ and $N(s)$ are equal to

$$D(s) = N_g(s)N_c(s) + D_g(s)D_c(s), \tag{21}$$

$$N(s) = N_g(s)N_c(s), \tag{22}$$

$\deg(D(s)) > \deg(N(s))$ and polynomial $D(s)$ is Hurwitz. Now, by considering a limit to the time delay in communication channel, a theorem will be given. If time delays T and $\tilde{T}$ are small enough, then the performance of the control system with the closed-loop transfer function given in (18) is equal to the performance of a delayed system with time delay equal to $(\tilde{T} - T)$ [22]. Furthermore, Brooks [23] proposed a bandwidth between 4-10 Hz for teleoperation systems. Consequently, by using the following first-order approximation for time delay in Laplace transform

$$e^{-Ts} = 1 - Ts, \tag{23}$$

$$e^{-\tilde{T}s} = 1 - \tilde{T}s, \tag{24}$$

we can calculate $\left|e^{-T(jw)}\right| = \left|1 - T(jw)\right| = \sqrt{1 + T^2 w^2} = 1$ which yields T=0.001 sec for time delay in communication channel. Therefore, when we refer to small time delay in communication channel, we mean a time delay approximately equal to 0.001 sec. Substituting these equations into the characteristic equation of control system given in (18) yields

$$\begin{aligned}\Delta_d(s) &= 1 + C_m(s)G(s) + C_m(s)G(s)(e^{-sT} - e^{-s\tilde{T}}) \\ &= 1 + C_m(s)G(s) + C_m(s)G(s)(1 - sT - 1 + s\tilde{T}) \\ &= 1 + C_m(s)G(s) + C_m(s)G(s)(s\tilde{T} - sT)\end{aligned}$$

$$= 1 + C_m(s)G(s)[1 - s(T - \tilde{T})]$$

$$= 1 + C_m(s)G(s)e^{-s(T-\tilde{T})}, \qquad (25)$$

***Theorem*:**

Let the estimation error for time delay in communication channel is denoted by $d = \tilde{T} - T$. Then, the proposed control system shown in Fig. 6 is stable for small time delays T and $\tilde{T}$, if

$$\left|\frac{N(s)}{D(s)}\right|_{s=jw} < 1 \qquad \forall w$$

where $D(s)$ is Hurwitz, $\deg(D(s)) > \deg(N(s))$, $D(s) = N_g(s)N_c(s) + D_g(s)D_c(s)$, $N(s) = N_g(s)N_c(s)$, $N_g(s)$ and $D_g(s)$ are the numerator and denominator of the no delay transfer function $G(s)$, respectively, and $N_c(s)$ and $D_c(s)$ are the numerator and denominator of $C_m(s)$, respectively.

***Proof*:**

By substituting $G(s) = \frac{N_g(s)}{D_g(s)}$ and $C_m(s) = \frac{N_c(s)}{D_c(s)}$ in (25) we have

$$\Delta_d(s) = 1 + C_m(s)G(s)e^{s(\tilde{T}-T)}$$

$$= D(s) + N(s)e^{-s(T-\tilde{T})}, \qquad (26)$$

Now, using above equation and $d = \tilde{T} - T$, equation (18) can be written as

$$M_d(s) = \frac{C_m(s)G(s)e^{-sT}}{1 + C_m(s)G(s) + C_m(s)G(s)(e^{-sT} - e^{-s\tilde{T}})}$$

$$= \frac{C_m(s)G(s)e^{-sT}}{1 + C_m(s)G(s)e^{-s(T-\tilde{T})}} = \frac{N(s)e^{-sT}}{D(s) + N(s)e^{-sd}}$$

$$= \frac{N(s)e^{-sd}}{D(s) + N(s)e^{-sd}} e^{-s(T-d)}, \qquad (27)$$

Since $e^{-s(T-d)}$ doesn't play any role in the stability of the closed-loop system, then, according to Tspkin theorem [24], the condition for closed-loop stability is

$$\left|\frac{N(s)}{D(s)}\right|_{s=jw} < 1 \qquad \forall w, \qquad (28)$$

which completes the proof.

VII. SIMULATIONS

In order to evaluate the effectiveness of the proposed control scheme in this paper, the controller has been applied to a simple teleoperation system. Two mechanical arms have been used as the master and slave systems

$$(M_m s^2 + B_m s)X_m = F_m + F_h$$

$$(M_s s^2 + B_s s)X_s = F_s - F_e$$

where B is the viscose friction coefficient, M is the manipulators inertia, X is the position and F is the input force; Indices m and s are for the master and the slave systems, respectively; F_h is the force applied to the master by human operator and F_e is the force exerted on the slave by its environment. The numeric values of the simulation parameters have been given in Table I. In simulations, two different conventional controllers are designed. The first one is a conventional PD controller, called remote controller, which have been used for the local slave controller. The second one is a conventional PD controller, called local controller, which have been used for the local master controller. Notice that the remote controller is designed such that $\hat{G}(s)$ is stable and the local controller is designed such that behaviour of teleoperation system is admissible. Furthermore, the master and the slave outputs can be considered position or velocity. In simulations, small random and varying time delay was used in communication channel, as it is shown in Fig. 8. Simulations have been executed for two different inputs. The first input is a step and the second input is a repeating pulse. Figs. 9 and 10 show the force tracking and the position tracking for master and slave, with small time varying delay in communication channel. As these Figures show, the proposed method has effectively controlled the system by considering transient and steady-state responses, in order to achieve transparency and stability for the teleoperation system.

VIII. CONCLUSION

In this paper, a new structure was proposed to achieve transparency and stability for teleoperation systems with small time delay uncertainty in communication channel. Two controllers, one in the master side and one in the slave side was design based on compliance control and direct force-measurement force-reflection control method, such that the local slave controller guarantees position/velocity tracking as the local master controller guarantees the force tracking and stability of the overall system. By using two classical and simple controllers (i.e., PD for position/velocity and force tracking) it was shown that the new control scheme is a practical choice for teleoperation systems with small time varying delay in communication channel, because the stability of the closed-loop system is guaranteed.

TABLE I
MODEL PARAMETERS

Symbol	Quantity
M_m = 0.4 kg	inertia of master
M_s = 1 kg	inertia of slave
B_m = 3 N/m	linear friction of master
B_s = 0.2 N/m	linear friction of slave
Z_e = 1	environment impedance

The advantage of the proposed method is that one can use the classical control methods as well as modern intelligent control methods. Furthermore, stability of teleoperation system can be checked graphically with bode plot method; hence, the controller design would be simple. Future works in this area will include considering large time varying delay as well as model uncertainty and providing more analytical work and conditions for stability of the closed-loop system.

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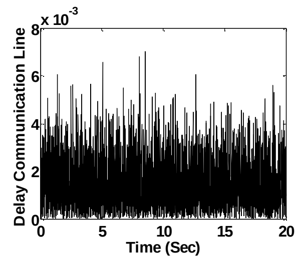

Fig.8. Time delay in communication channel

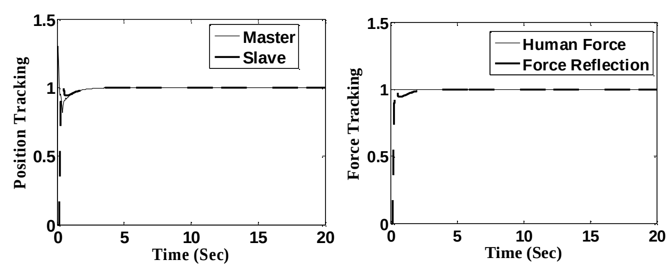

Fig.9. Position tracking and force tracking for step input

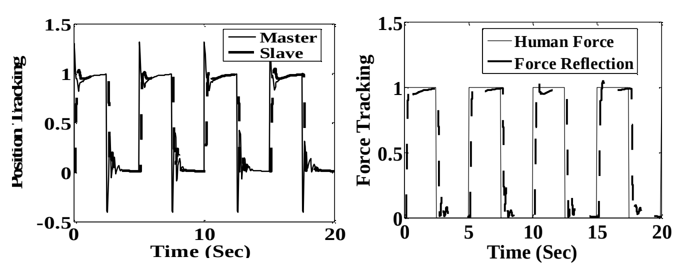

Fig.10. Position tracking and force tracking for repeating pulse