Bilateral Transparent Teleoperation with Long Time-Varying Delay: New Control Design and Stability Analysis

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Abstract—**This paper presents a novel structure design for bilateral teleoperation control systems with large varying time delay in communication channel. The goal of this paper is to achieve transparency and stability of the closed-loop system. To achieve transparency, two local controllers are designed for bilateral teleoperation. One local controller is responsible for tracking the master commands and the other local controller is in charge of force tracking as well as guaranteeing the stability of the closed-loop system in presence of varying time delay in communication channel. A neural network estimates this time delay. In addition, the stability of the closed-loop system, despite estimation error in neural network, will be shown by some analytical work. The advantages of the proposed method are stability, simple design of the local controllers, and transparency of the system. As a result, the designer has the flexibility to choose classical methods as well as intelligent controllers for local controllers. Simulation results show very good performance of the proposed method. Furthermore, the stability of teleoperation system can be checked graphically with bode method. Hence, the controller design would be simple.**

I. Introduction

Teleoperation robots (known as "telerobotics") are used for the carrying out complex tasks in hazardous and unknown (or partially known) environments such as radio active areas in nuclear power stations [1]. Telerobotics take advantage of human remote control with the autonomy of industrial robots. The main components of a telerobotic system are: 1) a set of two robots, referred to as the "local master robot" (or "master" for short) and the "remotely located slave robot" (or "slave" for short), 2) communication channel, 3) human operator, and 4) task environment. The master robot is directly driven by the human operator in its own local environment, whereas the slave robot is located in the remote environment, ready to follow human operator commands by moving the master. In bilateral control method, the remote environment gives some necessary information through the feedback loop to the local site as well. Additionally, a telerobotic system is said to be bilateral if the information signal flows in both directions between master and slave [2]. In this case, the performance of the telerobotic system is enhanced since the human operator receives information from the contact force on the slave side. A traditional way of providing this information, which is called force-reflecting control in teleoperation systems, is to reflect the contact force to the master robot. In this way, the overall performance can be improved, even better than visual and/or audio information [3]. Considering the time delay in communication channels and the uncertainty from the task environment, there are two major issues in telerobotic systems: 1) stability robustness and 2) transparency performance.

The communication channel plays an important role when the distance between the master and slave robot is too long. In these cases, a time delay in communication channel appears in information transmission that can not be ignored. In this case, due to the existence of time delay in the information transmission between the local and the remote site, the performance of the bilateral telerobotic systems will be degraded and can even lead to instability of the remotely-controlled manipulator [4]. To overcome the time delay problem, different teleoperation control systems have been proposed in literature such as the passivity theory [5], compliance control [6], wave variables [7], adaptive control [8] and robust control [9]. Transparency is also an important issue in telerobotic systems. If the human operator feels that he is directly interacting with the task, the telerobotic systems is called transparent [10]. Several papers have considered transparency of teleoperation system [11], [12]. But, they could make the system transparent only when the communication time delay was neglected. In practice, due to the existing delays in the communication channel and uncertainty in task environment, transparency and stability are significantly compromised [13]. In this paper, time-varying delay in communication channel is taken into account to design a bilateral telerobotic system. Furthermore, the ideal responses (i.e. the transparency) for the telerobotic system with time-varying delay in communication channel are definite as follows [10]:

- The force that the human operator applies to the master robot is equal to the force reflected from the environment in the steady state. This can help operators to realize force sensation.
- The master velocity/position is equal to the slave velocity/position in the steady state.

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.

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II. General Definitions

A two-port network can be used to model a teleoperation system by using the equivalence between mechanical systems and electrical circuits. In Figure 1, the teleoperation system is modeled as a two-port network, where the operator-master interface is designated as the master port and the slave-environment interface as the slave port. The environment is considered as the impedance Z_e.The relationship between efforts (f_h and f_e) and flows ($\dot{x}_m$ and $\dot{x}_s$) of the two ports can be described in terms of the so-called hybrid matrix. The hybrid matrix for the teleoperation system and its parameters are as follows [14]

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

where $F_h(s)$, $F_e(s)$, $V_m(s)$ *and* $V_s(s)$ are the Laplace transform of f_h, f_e, $\dot{x}_m$ and $\dot{x}_s$, respectively. The equation relating the contact force to the slave position can be derived as

$$F_e = Z_e V_s \tag{2}$$

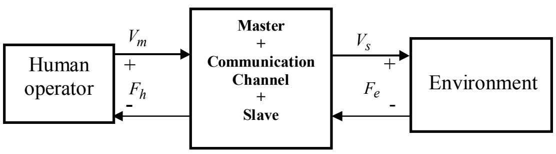

Fig. 1. Two-part model of teleoperation systems

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 are unity. So, for ideal one-degree-of-freedom teleoperation system, the **H** matrix is

$$\mathbf{H}_{\text{ideal}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{3}$$

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 Figure 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 in this paper, the compliance control and direct-force measurement-force reflecting control have been combined together in one block. In compliance control scheme, contact forces are used at the slave robot. 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.

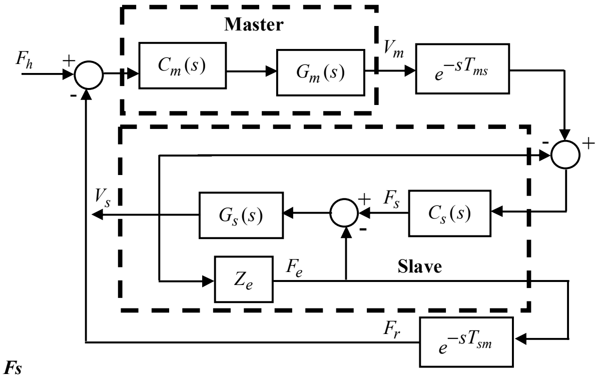

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Fig. 2. The proposed control scheme (the first form)

IV. Design of Control Schemes

A. Local slave controller

Based on the compliance control method, we propose the local slave controller. If it is assumed that the output of master and slave robot is velocity. Then, from Figure 2, the transfer function from the slave to the master can be written as

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

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.

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:

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

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

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

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

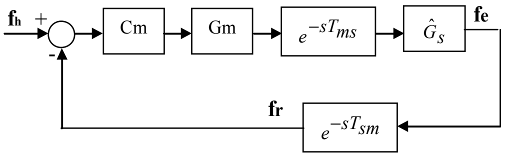

Fig. 3. New control scheme (the second form)

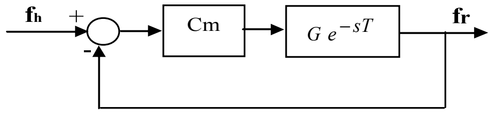

Fig. 4. New control scheme (the third form)

Using these variables, the control scheme, shown in Figure 2, can be simplified as Figure 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 Figure 3. Let's define this new output as F_r. So, the system shown in Figure 3 can be represented as the system in Figure 4. From Figure 4, the transfer function of the overall closed-loop system can be written as

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

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 [15].

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

In other words, using the Smith predictor, 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 1) the time delay must be constant, and 2) the model must be known precisely. As it is well known, it is hard to get the precise model of a teleoperation system. Moreover, the system parameters usually change with time. This will lead to some differences between the predictive model and the real plant, which is called mismatched model. In addition to that, the time delay is not constant.

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

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

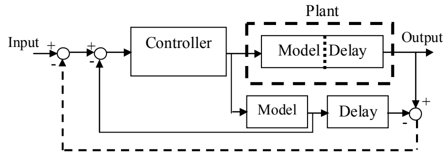

Fig. 5. The Smith predictor control scheme

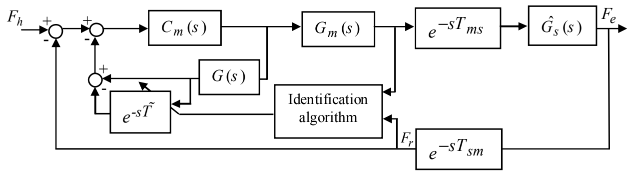

Fig. 6. Structure of Local Master Controller

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, a neural network has been used in this paper. This network acts as an adaptive filter by minimizing the mean squared error. In other words, the neural network 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. Figure 7 shows this neural network. The weight vector is updated according to the Least-Mean-Square (LMS) algorithm

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

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

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

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 network can be calculated as

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

In order to estimate the time delay, we have employed the algorithm in [16], in which the time delay is modeled 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:

$$y(t) = g(t-T) + \varphi(t) \quad (13)$$

$$x(t) = g(t) + \Phi(t) \quad (14)$$

where $\varphi(t)$ 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 σ^2. Then, the output of the neural network is [17]

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

and the weights can be calculated as

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

where

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

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 $\varphi(t)$ 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 [18]; 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.

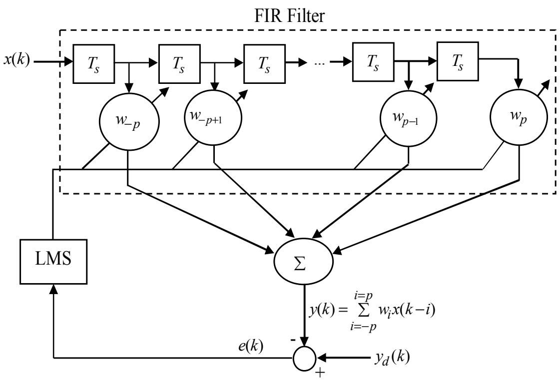

Fig. 7. Adaptive Time Delay Estimation

VI. Stability Analysis

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

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

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

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

Now, the problem is to find δ 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

$$M_\delta(s) = \frac{N(s)e^{-sT}}{D(s) + N(s)e^{-sT}(1 - e^{-s\delta})} \tag{20}$$

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.

Theorem:

The closed-loop control system, presented in Figure 6, is stable for any estimation error in $\tilde{T}$, if

$$\left|\frac{N(s)}{D(s)}\right|_{s=j\omega} < \frac{1}{2} \qquad \forall \omega$$

where $D(s)$ and $N(s)$ have been given in equations (21) and (22), respectively, $D(s)$ is Hurwitz, $\deg(D(s)) > \deg(N(s))$, $N_g(s)$ 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:

For proof, we use the method of two-dimensional stability test [19]. In this testing method, the system must be stable for $T = 0$ (i.e. no time delay in communication channel), which is true for the closed-loop system in Figure 6, since polynomial $D(s)$ is Hurwitz.

Now, the equations in two-dimensional stability test, which are solved simultaneously, can be rewritten as follows, using characteristic equation of the closed loop system $\Delta_\delta(s) = D(s) + N(s)(e^{-sT} - e^{-s\tilde{T}})$ and $z = e^{-sT}$:

$$\Delta_\delta(s, z, \tilde{z}) = 0 \tag{23}$$

$$\tilde{\Delta}_\delta(s, z, \tilde{z}) = \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1}) = 0 \tag{24}$$

Substituting characteristic equation in the recent equations give

$$\Delta_\delta(s, z, \tilde{z}) = D(s) + N(s)(z - \tilde{z}) = 0 \tag{25}$$

$$\begin{aligned}\tilde{\Delta}_\delta(s, z, \tilde{z}) &= \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1}) \\ &= D(-s) + N(-s)(z^{-1} - \tilde{z}^{-1}) \\ &= D(-s) + N(-s)(\frac{1}{z} - \frac{1}{\tilde{z}}) \\ &= z\tilde{z}D(-s) + N(-s)(\tilde{z} - z) = 0\end{aligned} \tag{26}$$

where $\tilde{z} = e^{-s\tilde{T}}$. From (25) we have

$$z = \tilde{z} - \frac{D(s)}{N(s)} \quad (27)$$

Substituting into (26) yields

$$\tilde{\Delta}_\delta(s, z, \tilde{z}) = \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1})$$
$$= \Delta_\delta(-s, [\tilde{z} - \frac{D(s)}{N(s)}]^{-1}, \tilde{z}^{-1}) \quad (28)$$
$$= \tilde{z}\left[\tilde{z} - \frac{D(s)}{N(s)}\right] D(-s) + N(-s)\left[\frac{D(s)}{N(s)}\right] = 0$$

Hence, we have

$$\tilde{\Delta}_\delta(s, z, \tilde{z}) = \tilde{z}^2 N(s) D(-s) - \tilde{z} D(s) D(-s) - N(-s) D(s) = 0 \quad (29)$$

And from there, we get

$$\tilde{z}^2 - \tilde{z}\frac{D(s)}{N(s)} + \frac{N(-s)D(s)}{N(s)D(-s)} = 0 \quad (30)$$

The roots of the recent equation, for $s = j\omega$ and $\tilde{z} = e^{-j\omega\tilde{T}}$, must lie in the left-hand side of the *S*-plane. To show this, consider equation (29) again

$$\frac{N(s)}{D(s)}\tilde{z}^2 - \tilde{z} + \frac{N(-s)}{D(-s)} = 0 \quad (31)$$

Substituting $\tilde{z} = e^{-j\omega\tilde{T}}$ and $s = j\omega$ in equation (31) gives

$$\frac{N(j\omega)}{D(j\omega)} e^{-2j\omega\tilde{T}} - e^{-j\omega\tilde{T}} + \frac{N(-j\omega)}{D(-j\omega)} = 0 \quad (32)$$

Factoring out $e^{-j\omega\tilde{T}}$ and recognizing that $\left|e^{-j\omega\tilde{T}}\right| \neq 0$, we have

$$e^{-j\omega\tilde{T}}\left[\frac{N(j\omega)}{D(j\omega)} e^{-j\omega\tilde{T}} - 1 + \frac{N(-j\omega)}{D(-j\omega)} e^{j\omega\tilde{T}}\right] = 0 \quad (33)$$

which gives

$$\frac{N(j\omega)}{D(j\omega)} e^{-j\omega\tilde{T}} + \frac{N(-j\omega)}{D(-j\omega)} e^{j\omega\tilde{T}} = 1 \quad (34)$$

Using the polar form, it gives

$$\frac{N(j\omega)}{D(j\omega)}[\cos\omega\tilde{T} - j\sin\omega\tilde{T}] + \frac{N(-j\omega)}{D(-j\omega)}[\cos\omega\tilde{T} + j\sin\omega\tilde{T}] = 1 \quad (35)$$

Knowing that in polar form, the amplitude is an even function, while phase is an odd function, we can conclude

$$2\left|\frac{N(j\omega)}{D(j\omega)}\right| \cos\left(\omega\tilde{T} + \measuredangle\frac{N(j\omega)}{D(j\omega)}\right) = 1 \quad (36)$$

Hence, if the condition $\left|\frac{N(j\omega)}{D(j\omega)}\right| < \frac{1}{2}$ is satisfied for all frequencies, the characteristic equation of the closed-loop transfer function, given in (20), won't have any roots with positive value for real parts, which yields to stability of the system, shown in Figure 6, independent of the value of $\tilde{T}$.

Remarks:

In the proof of the above theorem, it was shown that the condition for stability of the closed-loop system is

$$\left|\frac{N(j\omega)}{D(j\omega)}\right| < \frac{1}{2} \quad (37)$$

It is obvious that for a linear system it is always possible to design the local controllers such that: 1) they are stable, 2) the closed-loop system is transparent, and 3) the above inequality holds. Hence, using the proposed control method, stability can always be assured.

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

$$(M_m s^2 + B_m s)x_m = F_m + F_h$$
$$(M_s s^2 + B_s s)x_s = F_s - F_e$$

in which 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 at the master by the human operator and F_e is the force exerted on the slave by its environment. The numeric values of the simulation parameters are in Table 1. In simulations, two different conventional controllers are designed. The first one is a conventional PI controller, called remote controller, which have been used for the local slave controller. The second one is a conventional PI 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 behavior of teleoperation system is admissible. Furthermore, by checking the Bode plot of this system it can be seen that the stability condition in (37) holds. In simulations, we have used two different inputs: 1) Step input 2) sinusoidal input. A random number represents the varying time delay in communication channel (Figure 8). Figure 9 and 10, show that the force tracking and the–position tracking for master and slave with varying time delay in communication channel. As these Figures show, the proposed method has effectively controlled the system in transient state as well as in steady-state.

VIII. CONCLUSION

To achieve transparency and stability for a teleoperation system with large and varying time delay in communication channel, a new control scheme was proposed in this paper. Two local controllers, one in the master side and one in the slave side was design, such that the slave controller guarantees the position tracking and the master controller guarantees force tracking as well as the stability of the closed-loop system. The advantage of the proposed method is that one can use the classical control methods as well as modern intelligent control methods for these controllers. In this paper, by using two classical controllers (i.e., PI for position and force tracking and stability of the overall system) it was shown that the proposed control scheme is a viable choice for teleoperation systems with varying time delay in communication channel. Future works in this area will include considering mismatch model in teleoperation system and some analytical work and conditions for stability of the closed-loop system.

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TABLE I

MODEL PARAMETERS

Value	Parameters
0.4 kg= M_m	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

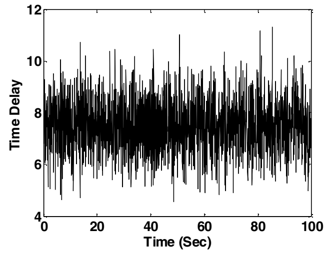
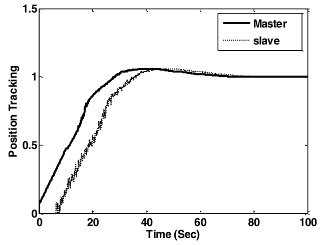
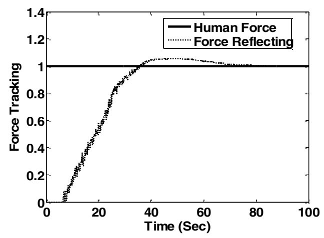


Fig.8. Time delay in communication channel

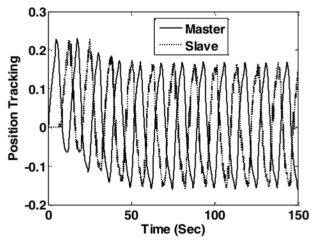


a)

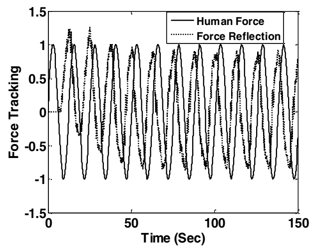


b)

Fig. 9. Transparency response for step input, (a) position tracking, (b) force tracking.



a)



b)

Fig. 10. Transparency response for sinusoidal input, (a) position tracking, (b) force tracking.