Bilateral Control of Teleoperation Systems with Bounded Uncertain Time Delay

A. Alfi and M. Farrokhi

Abstract—**In this paper, a new structure for bilateral teleoperation systems with bounded uncertain time delay in communication channel is proposed. The main contributions of the proposed method are two folds: 1) complete transparency for the system and 2) stability robustness. Moreover, due to the proposed structure, stability can be checked graphically using simple classical control methods, such as Bode plot. The key features of this structure are its simple design as well as the ability to analyze the stability of the closed-loop system using the property of the stable scalar functions and the small gain theorem. In the proposed structure, two local controllers will be designed, such that the transparency of the teleoperated system and the local stabilities are guaranteed. One local controller will be designated for position tracking of the slave system and the other one, whilst ensuring the stability of the closed-loop system in presence of uncertain time delay in communication channel, performs the force tracking. Simulation results demonstrate that the proposed control method is highly effective in providing a stable transparent teleoperation system under uncertain, but bounded, time delay in communication channel.**

Index Terms—**Bilateral teleoperation, uncertain time delay, transparency, force reflection.**

I. Introduction

TELEOPERSTION is one of the important fields in robotic. The concept of teleoperation means manipulating in a remote task environment with a slave manipulator controlled by a master manipulator moved by the human operator without requiring direct physical contact between human operator and task environment. During the last two decades, teleoperation systems have been used to allow human operators to execute tasks in hazardous environments, such as handling radioactive materials and maintenance of power units in nuclear plants; or to perform tasks in unreachable places, such as exploring and exploiting seas and seabeds and more recently in health care [1]. A teleoperation system consists of five different parts, as shown in Fig. 1: master system, communication channel, slave system, human operator, and task environment.

The master is directly driven by the human operator in the local environment, whereas the slave is located in the remote environment, ready to follow commands that human operator orders by moving the master. The communication channel and interactions between the remote environment and the slave are of important matter. If the force exerted on the slave by the remote environment

Manuscript received July 29, 2006; revised May 15, 2007.

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Publisher Item Identifier S 1682-0053(08)1540

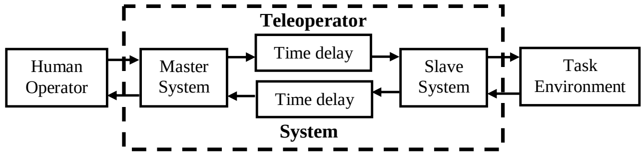

Fig. 1. The general structure of a teleoperation system.

can be feedback to the master robot and applied to the human operator, which is called force-reflecting control in teleoperation systems, the overall performance can be improved [2].

When the distance between the master robot and slave robot is too long, a significant time delay in communication channel appears that cannot be ignored. This time delay can destabilize the bilateral teleoperation system [3]. To solve this problem, different control schemes have been proposed in literatures. The most widely used control schemes are the passivity theory [4], compliance control [5], wave variables [6], adaptive control [7], and robust control [8].

In all literatures on teleoperation systems, transparency is a major criterion for performance in presence of time delay in communication channel as well as stability of the closed-loop system. If the slave accurately reproduces the master's commands and the master correctly feels the slave forces, then the human operator experiences the same interaction as the slave would. This is called transparency in teleoperation system [9]. In other words, a teleoperation system is called transparent if the following conditions are satisfied [10]:

1. Position/velocity tracking is guaranteed. The position/velocity tracking means that the slave output has to follow the master output in the steady state. Notice that the master and the slave outputs can be considered position or velocity.
2. Force tracking is also guaranteed. That means the reflecting force has to follow the human operator force in the steady state.

Recently, authors of this paper proposed new structure design for bilateral transparent teleoperation in presence of time delay [11]-[15]. In continuation of this research, a novel control method for bilateral teleoperation systems with uncertain, but bounded, time delay in communication channel is proposed in this paper. In the proposed structure, to achieve transparency, force measurement is used at the slave site, and force feedback (i.e. direct force-measurement force-reflecting control method) is used at the master site. Simulation results show good performance of the proposed method. The goal of this paper is three folds:

1. stability of the closed-loop system is guaranteed under some mild conditions

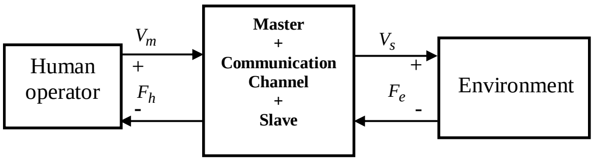

Fig. 2. Two-port model of teleoperation systems.

2. stability of the closed-loop system is guaranteed under some mild conditions
3. the whole system is transparent
4. design of local controllers is simple.

By applying independent controllers for the local and the remote sites, the designer has the option to select classical controllers for local systems. Hence, stability of the closed-loop system can be checked graphically with simple methods such as Bode plots.

The rest of this paper is organized as follows. Section II briefly describes general definitions of teleoperation systems. In Sections III and IV, the proposed control method is discussed. Section V analyses the stability of the proposed structure. In Section VI, modeling of teleoperation system is described. Section VII evaluates the proposed control method by simulations. Finally, Section VIII draws conclusions and gives some suggestions for the future work.

II. Definition of Transparency

A two-port network can be used to model a teleoperation system using the equivalence between mechanical systems and electrical circuits. In Fig. 2, a 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. In this figure, V_m and V_s denote the velocity of the master and the slave, respectively, F_e is the force exerted on the slave by its environment, and F_h is the force applied to the master by the human operator. Moreover, the interaction between the slave and the environment is modeled by considering the environment as an 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 [16]

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

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. The equation relating the contact force to the slave position can be derived as

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

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".

Using the scaling factors, the position/velocity command to the slave and the force command to the master can be modified such that

$$V_m = K_v V_s , \tag{3}$$

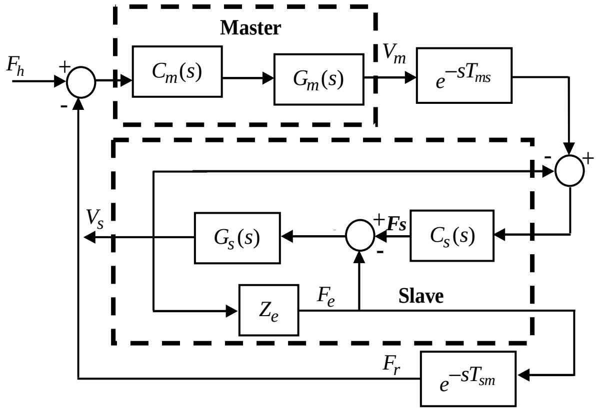

Fig. 3. Structure of the proposed control method.

$$F_h = K_f \; F_e , \tag{4}$$

where K_v and K_f are the position and force scaling factors, respectively. For ideal, one-degree-of-freedom teleoperation system, the $\mathbf{H}$ matrix is

$$\mathbf{H}_{ideal} = \begin{bmatrix} 0 & K_f \\ -K_v & 0 \end{bmatrix}. \tag{5}$$

III. The Proposed Control Scheme

Fig. 3 shows the proposed control scheme. In this figure, G and C denote the transfer function of the controllers, where subscripts m and s are used to designate the master and the slave, respectively. In addition, 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 reflected force. In the proposed method, the compliance control and direct force-measurement force-reflecting control scheme have been combined together [11]-[15]. Direct force-measurement force-reflecting control is a simple form of force-reflecting scheme using a force sensor in which the contact force is 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 (the slave robot) denoted by C_s, and the other one in local site (the master robot) denoted C_m. The remote controller guarantees the position/velocity tracking. That is, the slave has to follow the position/velocity of the master. The local controller guarantees the force tracking.

Furthermore, the local controller guarantees the stability of the overall system. Here, the scaling factors between master and slave are set to unity, and it is assumed that F_e is measurable. In the next sections, design of the local controllers will be described.

The following assumptions have to be stated first:

Assumption 1. The slave system acts in a non-free task environment.

Assumption 2. The forward and the backward time delays are identical.

Assumption 3. The contact force is measurable and available for the local controller.

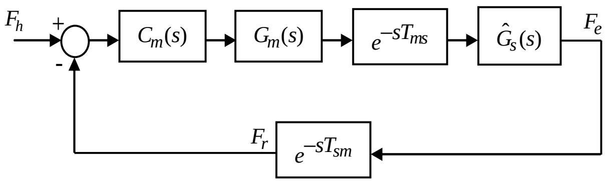

Fig. 4. New control scheme.

IV. Design of Controllers

In this section, design of the local controllers is presented. It should be mentioned that, due to the ideal response (i.e. complete transparency), between the master and the slave, scaling factors are set equal to one.

A. Local Slave Controller

According to Fig. 3, if the output of the master robot and the slave robots is velocity, then the transfer function from slave to master can be written as

$$\frac{V_s(s)}{V_m(s)} = \frac{C_s(s)G_s(s)}{1+Z_eG_s(s)+C_s(s)G_s(s)}e^{-sT_{ms}} \,. \quad (6)$$

Since the forward time delay does not appear in the denominator of the above equation, time delay will not have any effect on the stability. In addition, the classical control methods for linear systems, like PD, can be used to design a local slave controller C_s in the remote site such that system in (6) is stable. Therefore, 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, the local master controller, which can assure the stability of the closed-loop system as well as the force-tracking problem, will be proposed. The force tracking means the reflecting force has to follow the human operator force. Now, let define the following variables

$$\hat{G}_s(s) = \frac{Z_eC_s(s)G_s(s)}{1+Z_eG_s(s)+C_s(s)G_s(s)}, \quad (7)$$

$$G(s) = \hat{G}_s(s)G_m(s)\,, \quad (8)$$

$$F_r(s) = F_e(s)e^{-sT} \,. \quad (9)$$

Using these variables, the control scheme, shown in Fig. 3, is simplified as in Fig. 4. It can be 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).

Now, for force tracking, the contact force has to follow the human operator force. In most literatures, the forward and backward time delays are assumed identical [17]

$$T = T_{ms} = T_{sm} \quad (10)$$

Based on this assumption, the closed-loop transfer function of system given in Fig. 4 is equal to

$$M_c(s) = \frac{C_m(s)G(s)e^{-Ts}}{1+C_m(s)G(s)e^{-2Ts}} \,. \quad (11)$$

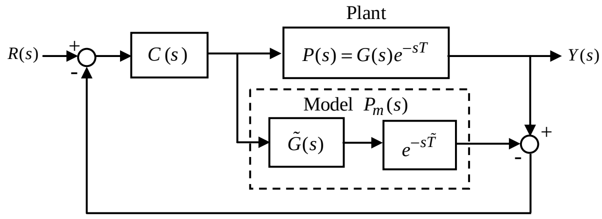

Fig. 5. Smith predictor control method.

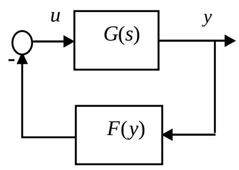

Fig. 6. A typical closed-loop system.

Notice that the roles of $M_c(s)$ are the stability of the overall system as well as the force tracking. Equation (11) shows that time delay is in the denominator of the closed-loop transfer function and can affect the overall performance of the system and may cause instability.

The Smith predictor is an effective method to solve this problem [18]. This predictor can effectively cancel out time delays from denominator of the closed-loop transfer function. In other words, using the Smith predictor, the system output is simply the delayed value of the delay-free portion of the system. Therefore, one can use the classical control methods for local master controller. Fig. 5 shows the general structure of a Smith predictor.

The main drawback of the Smith predictor is that the time delay must be constant [19]. However, it is possible that the time delay in communication channel is not constant.

This problem, in this paper, has been dealt with using linear scalar systems and small gain theorem as follows. The main feature of these systems is that their ∞ norms are bounded to unity [20]. Let define

$$\delta_1(s) = e^{-sT} \,, \quad (12)$$

$$\delta_2(s) = -\frac{1-e^{-sT}}{sT} \,, \quad (13)$$

such that

$$\|\delta_k(s)\|_\infty = \sup_{\mathrm{Re}\{s\}\geq 0} |\delta_k(s)| \leq 1 \quad , \quad k=1,2 \,. \quad (14)$$

Small Gain Theorem

Let a linear system with transfer function $G(s)$ be stable and the nonlinear map $F(y)$ be BIBO. Then, the closed loop system, shown in Fig. 6, is stable if

$$\gamma(G)\gamma(F) < 1 \,, \quad (15)$$

where $\gamma(F)$ is the gain of nonlinear map $F(y)$ and $\gamma(G) = \sup|G(j\omega)| \quad \omega \in \mathbb{R}$ [21].

Without lost of generality, the structure given in Fig. 4 can be rearranged as in Fig. 7, in which $G(s) = G_m(s)\hat{G}_s(s)$ and $T = T_{ms} = T_{sm}$. In addition, it is obvious that the stability of the proposed closed-loop model is the same as the stability of $M(s)$ (dashed rectangle in Fig. 7).

$$M(s) = \frac{\hat{F}_e}{F_h} = \frac{C_m(s)G(s)}{1+C_m(s)G(s)e^{-2Ts}} \quad (16)$$

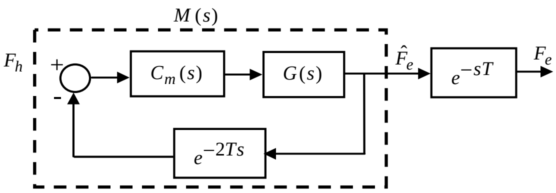

Fig. 7. Equivalent control structure for Fig. 4.

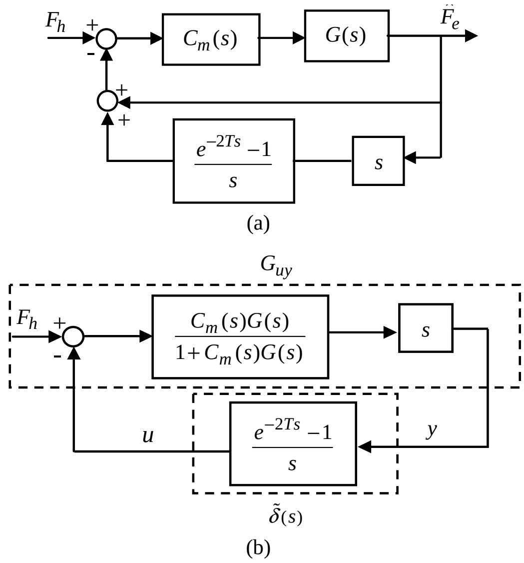

Fig. 8. The equivalent structure of $M(s)$ in Fig. 7.

and the transfer function of the entire system is

$$M_c(s) = M(s)e^{-Ts} = \frac{C_m(s)G(s)}{1+C_m(s)G(s)e^{-2Ts}}e^{-Ts} \quad (17)$$

Therefore, the local master controller must be designed to guarantee the stability of the closed-loop system $M_c(s)$, when the time delay in communication channel has some disturbances.

V. Stability Analysis

In this section, the stability of the proposed structure, as shown in Fig. 3, will be analyzed and the conditions, which satisfy this stability, will be given. According to section IV.B, the stability of the proposed closed-loop structure is equivalent to the stability of $M(s)$. In the followings, the stability theorem will be given, in which the stable scalar functions, (14), and the small gain theorem have been employed. Moreover, the uncertainties in the dynamics of the feedback system (i.e., the time delay in communication channel) will be modeled with δ_k (13).

Theorem:

Let a linear, time-invariant, and single-input-single-output control system be given as in Fig. 7, and let $G(s)$ be stable and the closed-system also be stable with no time delay ($T = 0$), then the closed-loop system $M(s)$ is stable, if [13]

$$\left|\frac{\omega C_m(s)G(s)}{1+C_m(s)G(s)}\right|_{s=j\omega} \le \frac{1}{2T_{\max}} \quad \forall\omega,\ 0 \le T \le T_{\max}. \quad (18)$$

Proof:

Let $M(s)$ in Fig. 7 be redrawn as in Figs. 8(a) and then 8(b). It is clear that the stability of structure in Fig. 8(b) is the same as the stability of $M(s)$.

Now, let $G_{uy}(s) = sC_m(s)G(s)/1+C_m(s)G(s)$. Then, according to the small gain theorem, the closed-loop system is stable if

$$\gamma(G_{uy})\gamma(\tilde{\delta}) < 1. \quad (19)$$

Considering the property of stable scalar functions $\|\delta(s)\|_\infty = \left\|1-e^{-2Ts}/2sT\right\|_\infty \le 1$ and assuming the worst case for delay time in communication channel $T = T_{\max}$, we have

$$\gamma(\tilde{\delta}) < 2T_{\max} \quad \rightarrow \quad |\gamma(G_{uy})| \le \frac{1}{2T_{\max}}. \quad (20)$$

Therefore,

$$|G_{uy}(j\omega)| = \left|\frac{\omega C_m(j\omega)G(j\omega)}{1+C_m(j\omega)G(j\omega)}\right| \le \frac{1}{2T_{\max}}. \quad (21)$$

This completes the proof.

Remark 1:

Considering (21), it is apparent that the smaller the values for time delay in communication channel, the simpler the design for local master controller to guarantee stability of the overall system as well as force tracking.

Remark 2:

In order to increase the robustness of the overall system, with uncertainty in time delay, one can design the local controller such that (21) is always valid. It should be noted that, there is a trade off between $|G_{uy}(j\omega)|$ and transparency. That is, making this magnitude too small might compromise the transparency. This fact is true in practice as well. In other words, due to the existing delays in communication channel and uncertainty in environment dynamics, there is a compromise between stability and transparency [9], [22].

Remark 3:

The local master and slave controllers are designed such that the stability condition in (21) is guaranteed. The coefficients for these controllers are not unique. The designer has a wide verity of selections for these coefficients. The only requirement is to satisfy the stability condition given in (21). However, selecting the magnitude $|G_{uy}(j\omega)|$ too small can compromise good transparency of the closed-loop system.

VI. Modeling of Teleoperation Systems

A. Slave Model

The Remote site has two parts: the slave manipulator and the environment where the task takes place. The slave, used as the teleoperation system, is usually a robotic manipulator with several Degrees of Freedom (DOF). The dynamic Model of an n DOF robotic manipulator is usually given as [23]

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{F}(\mathbf{q},\dot{\mathbf{q}}), \quad (22)$$

where $\boldsymbol{\tau} \in \Re^{n\times 1}$ is the torque vector produced by the actuators, $\mathbf{M}(\mathbf{q}) \in \Re^{n\times n}$ is the inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) \in \Re^{n\times 1}$ represents centrifugal and coriolis terms, $\mathbf{G}(\mathbf{q}) \in \Re^{n\times 1}$ is the gravitational load, and $\mathbf{F}(\mathbf{q},\dot{\mathbf{q}}) \in \Re^{n\times 1}$ represents the frictional load. For the purpose of illustration, consider a

TABLE I
MODEL PARAMETERS

Value	Parameters
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

TABLE II
PD CONTROLLERS COEFFICIENTS

Case	K_P	K_D
Case 1: T = 1 sec. and constant	0.75	0.45
Case 2: T = 1 sec. and constant T = 0.5 sec. for local controller	0.15	0.85
Case 3: Bounded uncertain time delay	0.7	0.5

one DOF robot with linear equations for the dynamics of the remote robot manipulator. Taking the interactions with the environment into account, yields

$$\tau - \tau_e = M_s \ddot{q} + F_s \dot{q} \tag{23}$$

where F_s is the linear friction and τ_e is the interaction torque between the manipulator end-effector and the environment.

B. Slave Model

The master used in a teleoperation system is affected by the human force. The dynamics of a single-DOF master manipulator is

$$M_m \ddot{x}_m(t) + B_m \dot{x}_m(t) = u_m \tag{24}$$

where M_m and B_m are the manipulator's inertia and damping coefficient. The force u_m applied to the Manipulator depends on the interaction with the human operator.

VII. SIMULATIONS

In order to evaluate the effectiveness of the proposed control scheme, as is shown in Fig. 3, the controller has been applied to the teleoperation system. In simulations, two mechanical arms have been used as the master and the slave systems. The dynamics of the master and the slave systems are described as a 1-DOF mass-damper system by

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

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

in which B is the viscous friction coefficient, M is the manipulator's inertia, X is the position, and F is the input force; indices m and s denote 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 system parameters have been given in Table I.

In simulations, two different conventional controllers are designed. The first one is a PD controller, called remote controller, which have been used for the slave. The second one is a PD controller, called local controller, which have been used for the master. Two different values for time delay in communication channel have been used:

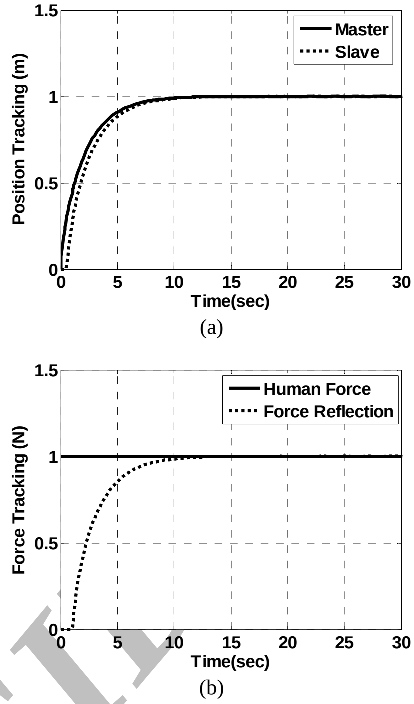

Fig. 9. Transparency response for case 1, (a) position tracking, and (b) force tracking.

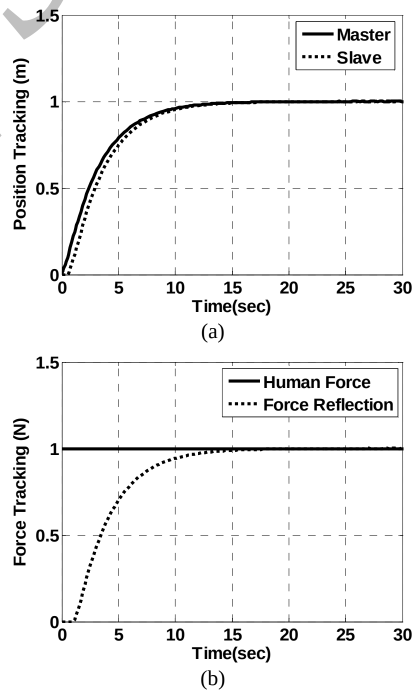

Fig. 10. Transparency response for case 2, (a) position tracking, and (b) force tracking.

1) constant time delay
2) perturbed time delay.

The PD coefficients for different cases have been shown in Table II. Notice that the remote controller is designed such that $\hat{G}(s)$ is stable and the local controller is designed such that the transparency of teleoperation system is admissible. Furthermore, the stability condition of the closed-loop system in (18) must hold.

Simulations for the proposed method are carried out for three cases. In cases I and II, the time delay in communication channel is fixed and equal to one second. In case III, the time delay is bounded with some perturbations. The simulation results are given in

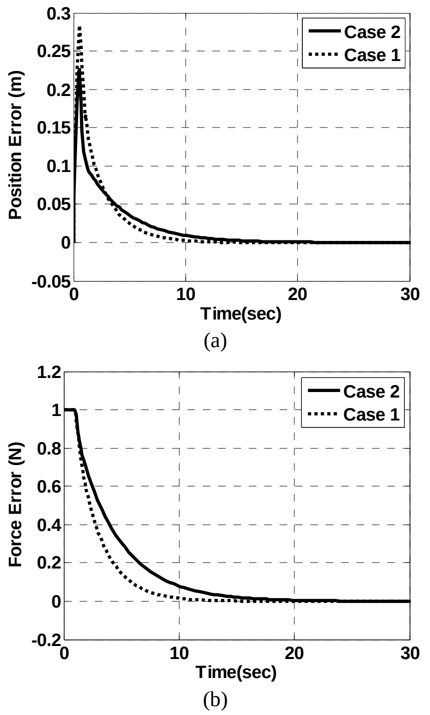

Fig. 11. Error response for case 1 and case 2, (a) position error, and (b) force error.

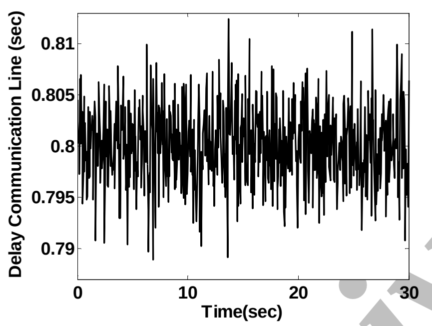

Fig. 12. Uncertain time delay in communication channel.

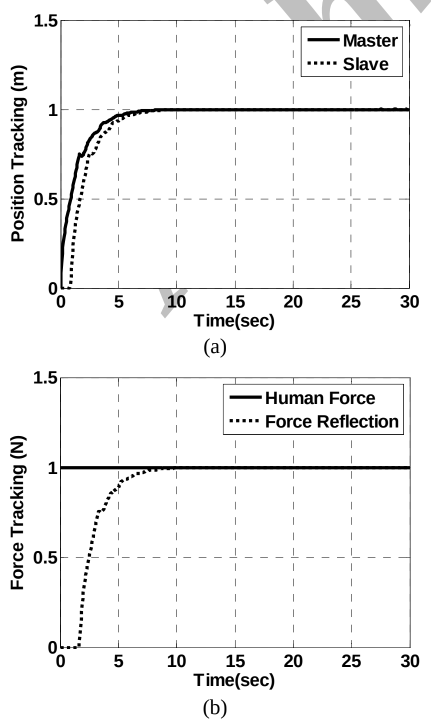

Fig. 13. Transparency response for case 3, (a) position tracking, and (b) force tracking.

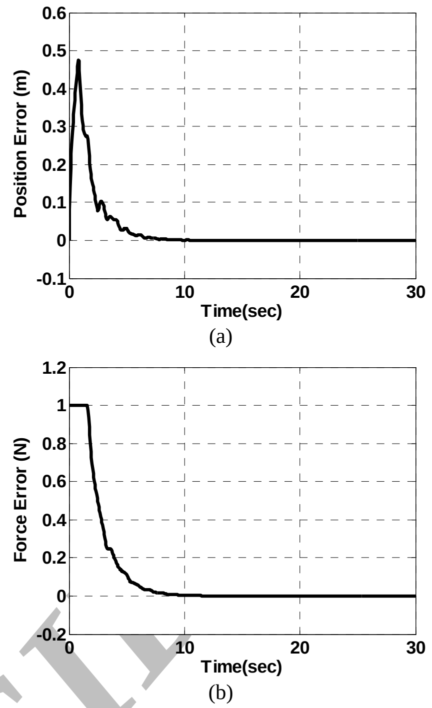

Fig. 14. Error response for case 3, (a) position error, and (b) force error.

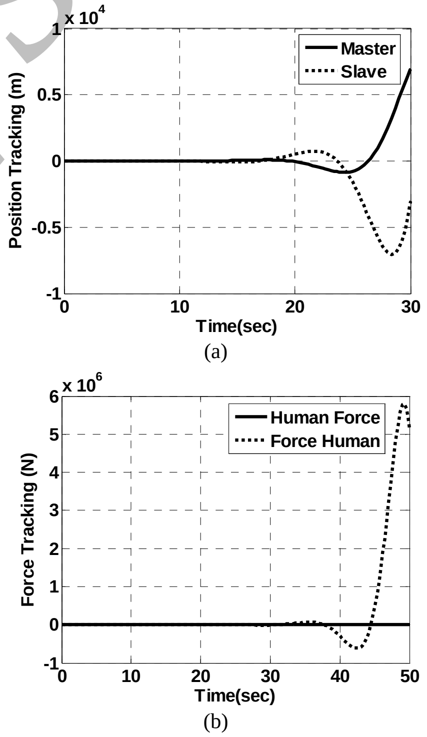

Fig. 15. Unstable teleoperation system without controller, (a) position tracking, and (b) force tracking.

Figs. 9-15. As Fig. 9 shows, the proposed structure exhibits good performance both for stability as well transparency of the closed-loop system for case I. In order to verify *Remark 2*, the performance of the proposed structure is shown in Fig. 10 for maximum time delay equal to one second. In this case, design of the controller is based on (21) for fixed time delay equal to 0.5 sec. According to *Remark 2*, although the closed-loop system is stable and transparent, the settling time is more than the previous case. Fig. 11 presents the error response for cases I and II. This Figure confirms good performance of the proposed control structure.

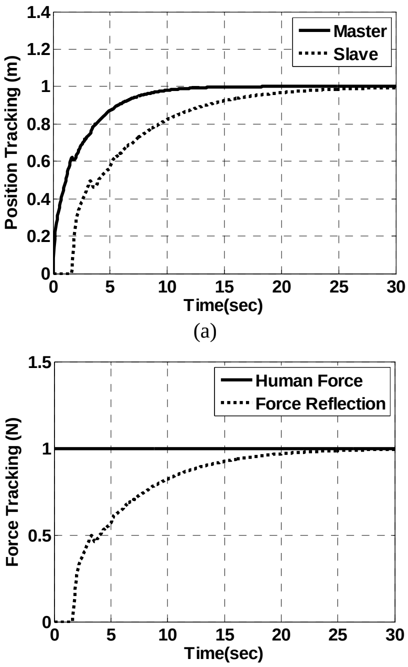

Fig. 16. Transparency response in presence of the time delay with the same coefficients for local controllers for case 1 given in table II, (a) position tracking, (b) force tracking.

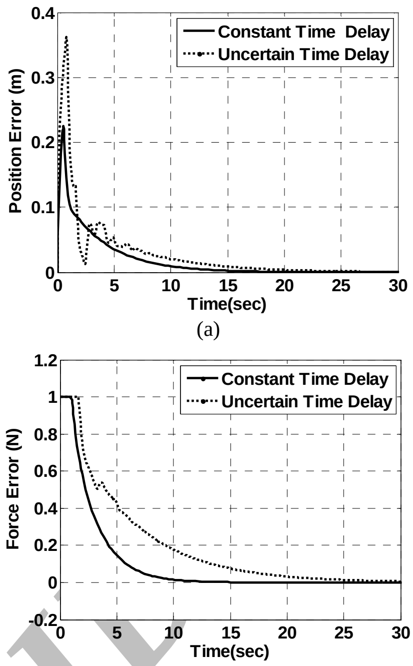

Fig. 17. Error Response in presence of the constant and uncertain time delay with the same coefficients for local controllers for case 1 given in table II, (a) position error, and (b) force error.

In case III, to show the performance of the proposed controller against bounded uncertain time delay, the teleoperation system is tested with the time delay shown in Fig. 12. Figs. 13 and 14 show the transparency response and error response for maximum time delay equal to one second, according to (21) in this case. Moreover, Fig. 15 presents an unstable teleoperation system without local controllers.

Recall that, in order to get good transparency, a designer has to tune the coefficients of the local controllers. This subject was explained in remark 3. However, in order to show the undesirable effects of the uncertain time delay on the transparency, the simulation is carried out against uncertain time delay using the same coefficients for case 1 given in table II. The simulation results are shown in Figs. 16 and 17. Although the system is still stable, the performance is worse than the case 1 (i.e. the case, where the time delay was assumed constant).

VIII. Conclusion

To achieve transparency and stability robustness for a teleoperation system with uncertain time delay in communication channel, a new control scheme was proposed in this paper. Two local controllers, one on the master side and the other one on the slave side was design such that the slave controller guarantees the position tracking and the master controller guarantees force tracking and as well as the stability of the closed-loop system. The major advantage of the proposed method is that one can use the classical control methods, such as PD, for local controllers. Furthermore, stability of teleoperation systems can be checked graphically with Bode plot method. Therefore, the controller design would be simple and straightforward. In this paper, by using two classical and simple controllers (i.e., PD for position and force tracking) it was shown that the proposed control scheme is a practical choice for teleoperation systems in order to avoid system instability due to perturbations in time delay in communication channel. Moreover, condition for stability of the closed-loop system was shown with some analytical work.

With the recent advances in communication networks, internet can be used as communication channel to transmit information from the local site to the remote site and vice versa. Hence, the time delay in communication channel varies. Moreover, the forward and the backward time delays may be not identical. Consequently, the proposed control method may be limited in practice. Future works in this area will include considering unbounded time delay in communication channel for proposed structure and some analytical work and conditions for stability robustness of the closed-loop system.

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