A Simple Structure for Bilateral Transparent Teleoperation Systems with Time Delay

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Abstract: This paper presents a simple structure design for bilateral teleoperation systems with uncertainties in time delay in communication channel. The goal is to achieve complete transparency and robust stability for the closed-loop system. For transparency, two local controllers are designed for the bilateral teleoperation systems. One local controller is responsible for tracking the master commands, and the other one is in charge of force tracking as well as guaranteeing the stability of the closed-loop system in presence of uncertainties in time delay. The stability analysis will be shown analytically for two cases: I) the possibly stability and II) the intrinsically stability. Moreover, in case II, in order to generate the proper inputs for the master controller in presence of uncertainties in time delay, an adaptive FIR filter is designed to estimate the time delay. The advantages of the proposed method are three folds: 1) stability of the closed-loop system is guaranteed under some mild conditions, 2) the whole system is transparent, and 3) design of the local controllers is simple. Simulation results show good performance of the proposed method.
Keywords: Teleoperation, Transparency, Stability, Time delay, Adaptive Filters

1. Introduction

Teleoperation is one of the important research areas in robotics. 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 the operator and the task environment. If the force exerted on the slave by the remote environment can be fed back to the master robot, which is called force-reflecting control in teleoperation systems, and this force in turn is applied to the human operator, then the overall performance can be improved [1].There are two major issues in bilateral teleoperation systems: 1) the stability robustness and 2) the transparency performance. 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 [2]. In other words, the ideal responses (i.e. the complete transparency) for the teleoperation operation system with time delay can be defined as follows:

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

In practice, due to the existing time delays in communication channel and uncertainties in the task environment as well as parametric uncertainties in robot manipulators, transparency and stability are significantly compromised. By considering these issues, different control schemes have been proposed in literatures. The most widely used control schemes are the passivity theory [3], wave variables [4], compliance control [5], and adaptive control [6].

Alfi et al. proposed a simple structure and control method for bilateral transparent teleoperation systems in presence of uncertainties in time delay [7-9]. In this method, a force sensor is used for reflecting the contact force to the human operator. The proposed structure takes advantage of two local controllers. One controller is responsible for tracking the master commands and the other one is in charge of force tracking as well as guaranteeing stability of the closed-loop system in presence of uncertainties in the time delay in communication channel. Therefore, the goal of this paper is two folds: 1) developing a simple structure to achieve complete transparency and 2) developing the stability conditions (intrinsic and possible) for the proposed structure in presence of uncertainties in time delay in communication channel.

In possibly stable, stability of the proposed structure dependents on the time delay in communication channel. On the other hand, in intrinsically stable, stability of the proposed structure is independent of the time delay. Moreover, in possibly stable, it is assumed that the forward and the backward time delays are identical. This constrain is removed in intrinsically stable. Furthermore, in the proposed control method, an identification algorithm is developed, which, in addition to estimate the time delay, makes the closed-loop system virtually independent of the time delay. In the rest of this paper whenever it is referred to "time delay", it means "time delay in communication channel".

This paper is organized as follows. In Section 2, the proposed control method is discussed. Section 3 describes design of the controllers. Analytical work about stability of the proposed structure is given in Section 4. Section 5 shows the simulation results. Section 6 draws conclusions and gives suggestions for the future work.

2. The Proposed Control Structure

The proposed control structure is shown in Fig. 1. In this Figure, G , C and y denote the transfer function of the local systems, the local controllers, and the outputs, respectively, where the subscripts m and s designate the master and the slave, respectively. T_{ms} and T_{sm} denote the forward and the backward time delay, respectively. F_e is the force exerted on the slave by its environment, Z_e is the environment impedance, F_h is the force applied to the master by the human operator, K_p and K_f are the position and force scaling factors, respectively, F_s is the input force applied to the slave, and F_r is the reflected force. To correct the desired position/velocity, received from the master, contact forces are used at the slave robot. Moreover, direct-force-measurement force-reflecting control method is used at the local sites. The main goal of the proposed control scheme is to achieve transparency and stability. This can be itemized as follows:

1- The closed-loop of the overall system must be stable with some mild and easy-to-achieve conditions.

2- The position/velocity tracking must be guaranteed. This means that the slave output y_s has to follow the master output y_m with acceptable accuracy. Notice that the master and the slave outputs can be considered either the position or the velocity.

3- Force tracking must be guaranteed. That means the reflecting force F_r has to follow the operator force F_h .

These goals are achieved by designing two local controllers; one in the remote site C_s guarantees the position/velocity tracking, and the other one in the local site C_m guarantees the force tracking as well as stability of the overall system. It is assumed that K_p and K_f are equal to one and F_e is measurable.

3. Controllers Design

In this section, design of the local controllers is explained. It should be mentioned that, due to the ideal response, i.e. complete transparency, the scaling factors are set equal to one.

3.1 The Slave Controller

For designing the slave controller C_s, force measurements are used at the remote site. According to Fig. 1, if the output of the master and the slave is position, then the transfer function from the slave to the master can be written as

$$\frac{X_s(s)}{X_m(s)} = \frac{C_s(s)G_s(s)}{1+Z_eG_s(s)+C_s(s)G_s(s)}e^{-sT_{ms}} \quad . \quad (1)$$

Since the forward time delay does not appear in the denominator, the transfer function in Eq. (1) is finite dimensional. Hence, the time delay will not have any effect on the stability of the system. Moreover, one can use the classical control methods to design a slave controller for the remote site, such that the system in Eq. (1) is stable. Therefore, the position of the slave will follow the position of the master in such a way that the tracking error for position converges to zero.

3.2 The Master Controller

The master controller $C_m(s)$ must assure stability of the closed-loop system as well as force-tracking problem. Let define the following variables:

$$\hat{G}_s(s) = \frac{Z_eC_s(s)\,G_s(s)}{1+Z_eG_s(s)+C_s(s)\,G_s(s)}\,, \quad (2)$$

$$G(s) = \hat{G}_s(s)\,G_m(s)\,. \quad (3)$$

Using these variables, the control scheme, shown in Fig. 1, can be simplified as in Fig. 2. Then, the transfer function of the overall closed-loop system can be written from Fig. 2 as

$$M(s) = \frac{F_e}{F_h} = \frac{C_m(s)G(s)e^{-T_{ms}}}{1+C_m(s)G(s)e^{-(T_{ms}+T_{sm})s}}\,. \quad (4)$$

Notice that the local slave controller C_s is designed such that the position tracking is satisfied (i.e., the poles of $\hat{G}_s$ are in the left-hand side of the *S*-Plane). From Eq. (4), it can be observed that the delays are in the denominator of the closed-loop transfer function. This can degrade performance of the system by reducing its stability margin. As a result, one cannot use the classical control methods to design a master controller. Hence, the problem is to handle the time delay properly, since time delay can significantly deteriorate the performance of the whole system or even makes it unstable. This issue will be addressed in the next section.

4. Stability Analysis

In this paper, two stability methods for teleoperation systems are considered: 1) the intrinsically stability and 2) the possibly stability. The intrinsically stability guarantees stability of the teleoperation system independent of the time delay; while possibly stability is referred to as the property in which the system is stable for any time delay values as long as $T \le T_{\max}$. Hence, the possibly criterion assumes a prior knowledge on the upper bounds of the delay values [10].

4.1. Possibly Stability

In this paper, the possibly stability is dealt with using linear scalar systems. The main feature of these systems is that their H_∞ norms are bounded to unity [11]. Let define

$$\delta_1(s) = e^{-sT} \;,\; \delta_2(s) = -\frac{1-e^{-sT}}{sT}\,, \quad (5)$$

such that

$$\|\delta_k(s)\|_\infty = \sup_{\mathrm{Re}(s)\ge 0} |\delta_k(s)| \le 1, \quad k=1,2 \quad (6)$$

In the following theorem, the stable scalar functions (6) and the small gain theorem will be employed. Moreover, the uncertainties in the dynamics of the feedback system will be modeled with δ_k. In addition, it is assumed that the forward and the backward time delays are identical. This assumption is commonly used in most literatures [12].

Theorem 1: Consider a control system as in Fig. 2 with $T = T_{ms} = T_{sm}$. Let $G(s)$ in (3) and the closed-system in Fig. 2 be stable with no time delay ($T = 0$). Then the closed-loop system is stable if

$$\left|\frac{\omega C_m(s)G(s)}{1+C_m(s)G(s)}\right|_{s=j\omega} \le \frac{1}{2T_{\max}} \quad \forall\omega,\ 0 \le T \le T_{\max}. \tag{7}$$

Proof: Without loss of generality, the structure given in Fig. 2 can be rearranged as in Fig. 3, in which $G(s)$ is defined in (3)**.** It is obvious that stability of the closed-loop block diagram in Fig. 3 (dashed rectangle designated with $\hat{M}(s)$) is the same as stability of $M(s)$ in (4). That is, $\hat{M}(s)$ can be written as

$$\hat{M}(s) = \frac{\hat{F}_e}{F_h} = \frac{C_m(s)G(s)}{1+C_m(s)G(s)e^{-2Ts}}. \tag{8}$$

Then, the transfer function of the entire system is

$$M(s) = \hat{M}(s)e^{-Ts} = \frac{C_m(s)G(s)}{1+C_m(s)G(s)e^{-2Ts}}e^{-Ts}. \tag{9}$$

Therefore, the master controller must be designed to guarantee stability of the closed-loop system $\hat{M}(s)$. Hence, it can be concluded that stability of the proposed closed-loop structure is equivalent to stability of $\hat{M}(s)$. Now, let $\hat{M}(s)$ in Fig. 3 be redrawn as in Figs. 4a and then 4b. It is clear that stability of the structure in Fig. 4b is the same as stability of $\hat{M}(s)$.

Now, let $G_{uy}(s) = \dfrac{sC_m(s)G(s)}{1+C_m(s)G(s)}$. Then, according to the small gain theorem [13], the closed-loop system is stable if

$$\gamma(G_{uy})\gamma(\tilde{\delta}) < 1. \tag{10}$$

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

$$\gamma(\tilde{\delta}) < 2T_{\max} \quad \rightarrow \quad |\gamma(G_{uy})| \le \frac{1}{2T_{\max}}. \tag{11}$$

Therefore,

$$|G_{uy}(j\omega)| = \left|\frac{\omega C_m(j\omega)G(j\omega)}{1+C_m(j\omega)G(j\omega)}\right| \le \frac{1}{2T_{\max}}. \tag{12}$$

This completes the proof. o

Remark 1: It should be noted that, there is a trade off between $\left|\dfrac{\omega C_m(j\omega)G(j\omega)}{1+C_m(j\omega)G(j\omega)}\right|$ and the transparency. That is, making this magnitude too small might compromise the transparency. This fact is also true in practical applications. That is, due to the existing delays in the communication channel and uncertainties in the environment dynamics, there is a compromise between stability and transparency [8].

4.2. Intrinsically Stability

Since force tracking is performed by sending the force contact through the reflection path of the communication channel, one can define F_r as a new output in the block diagram of Fig. 2. Then, this block diagram can be simplified as the block diagram in Fig. 5, from which the transfer function of the overall closed-loop system can be written as

$$M(s) = \frac{F_r}{F_h} = \frac{C_m(s)G(s)e^{-sT}}{1+C_m(s)G(s)e^{-sT}}, \tag{13}$$

where $T = T_{ms} + T_{sm}$ and $F_r(s) = F_e(s)e^{-sT_{sm}}$.

Notice that, the tasks of $C_m(s)$ are to provide stability of the overall system and to ensure force tracking. From (13), it can be seen that there is a delay in the denominator of the closed-loop transfer function; hence, it is infinite dimensional. Moreover, it can destabilize the system by reducing the system stability margin and degrading its performance. As a result, one cannot use classical control methods to design a master controller C_m such that overall system in (13) is stable. Therefore, the time delay must be dealt with properly.

The most popular and effective method to solve the delay problem for stable processes is the Smith predictor. This predictor can effectively cancel out time delays from the denominator of the transfer function of the closed-loop system. Fig. 6 shows block diagram of the Smith predictor. However, the main drawbacks of the Smith predictor are 1) the time delay must be constant and known a priori and 2) the model must be known precisely [14]. Hence, applications of the Smith predictor are limited in teleoperation systems. To overcome these limitations, it is necessary to find a mechanism to compensate for the mismatched model as well as uncertainties in the time delay. In order to compensate for the mismatched model, a second feedback loop is introduced in the closed-loop system (dashed line in Fig. 6). Furthermore, the time delay is be estimated adaptively. In this way, effects of the changes in the system will be completely compensated. Hence, proper inputs can be generated for the master controller.

Fig. 7 shows structure of the master controller. According to this Figure, the closed-loop transfer function can be written as

$$M(s) = \frac{C_m(s)G(s)e^{-sT}}{1+C_m(s)G(s)+C_m(s)G(s)[e^{-sT}-e^{-s\tilde{T}}]}, \tag{14}$$

where $G(s)$ is defined in (3). It is obvious that stability of the closed-loop system depends on the time delay. If the actual time delay T is equivalent to the estimated time delay $\tilde{T}$, then the closed-loop system is stable. Equation (14) can be written as

$$M(s) = \frac{C_m(s)\,G(s)\,e^{-sT}}{1 + C_m(s)\,G(s)} \tag{15}$$

Fig. 8 shows block diagram of the equivalent closed-loop system for $T = \tilde{T}$. However, due to estimation errors $T \neq \tilde{T}$. Hence, the closed-loop system may be unstable. In the rest of this paper, the stability conditions will be discussed for the case of $T \neq \tilde{T}$. Suppose, there exists estimation error for time delay and let $\tilde{T} = T + \delta$ denote the estimated time delay. The master controller C_m will be designed based on the estimated time delay. The closed-loop transfer function, given in (14), can be written as

$$M_\delta(s) = \frac{C_m(s)G(s)\,e^{-sT}}{1 + C_m(s)G(s) + C_m(s)G(s)\,e^{-sT}\,(1 - e^{-s\delta})}. \tag{16}$$

It is apparent that stability of the closed-loop system depends on the time delay. Now, the problem is to find the stability conditions such that the closed-loop system is stable. In other words, the roots of the characteristic equation lie in the left-hand side of the S plane. To do this, let show the no delayed version of $G(s)$ and $C_m(s)$ as

$$G(s) = \frac{N_g(s)}{D_g(s)}, \quad C_m(s) = \frac{N_c(s)}{D_c(s)}. \tag{17}$$

Then, the transfer function in (16) can be rewritten as

$$M_\delta(s) = \frac{N(s)e^{-sT}}{D(s) + N(s)e^{-sT}\,(1 - e^{-s\delta})}. \tag{18}$$

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

$$D(s) = N_g(s)N_c(s) + D_g(s)D_c(s) \tag{19}$$

$$N(s) = N_g(s)N_c(s), \tag{20}$$

in which $\deg(D(s)) > \deg(N(s))$ and polynomial $D(s)$ is Hurwitz. In the following theorem, the condition for stability of the closed-loop system without any upper bound for the time delay will be shown. That is, the time delay can be any limited value.

Theorem 2: The closed-loop system in Fig. 7 is intrinsically stable, i.e. independent of the estimated time delay $\tilde{T}$, if

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

where $D(s)$ and $N(s)$ are given in (19) and (20), respectively, $D(s)$ is Hurwitz, and

$$\deg(D(s)) > \deg(N(s)).$$

Proof: For proof, the method of two-dimensional stability (2-D) test is used here [11]. In this testing method, the system must be stable for $T = 0$ (i.e. stable for no time delay). This is true for the closed-loop system in Fig. 7, since polynomial $D(s)$ is Hurwitz. Now, using the characteristic equation of (18), the equations in 2-D test, which must be solved simultaneously, can be written as

$$\Delta_\delta(s) = D(s) + N(s)(z - \tilde{z}), \tag{21}$$

$$\Delta_\delta(s, z, \tilde{z}) = 0 \tag{22}$$

$$\tilde{\Delta}_\delta(s, z, \tilde{z}) = \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1}) = 0 \tag{23}$$

where $z = e^{-sT}$ and $\tilde{z} = e^{-s\tilde{T}}$.

Based on 2-D, when no solution for (22) and (23) exists; the closed-loop system given in (18) must be intrinsically stable. Using the characteristic, it yields

$$\Delta_\delta(s, z, \tilde{z}) = D(s) + N(s)(z - \tilde{z}) = 0, \tag{24}$$

and

$$\begin{aligned}\tilde{\Delta}_\delta(s, z, \tilde{z}) &= \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1}) \\ &= D(-s) + N(-s)(z^{-1} - \tilde{z}^{-1}) \\ &= z\,\tilde{z}\,D(-s) + N(-s)(\tilde{z} - z) = 0.\end{aligned} \tag{25}$$

From (24) it yields

$$z = \tilde{z} - \frac{D(s)}{N(s)}, \tag{26}$$

Substituting (26) into (25) gives

$$\begin{aligned}\tilde{\Delta}_\delta(s, z, \tilde{z}) &= \Delta_\delta(-s, z^{-1}, \tilde{z}^{-1}) \\ &= \Delta_\delta\left(-s, \left[\tilde{z} - \frac{D(s)}{N(s)}\right]^{-1}, \tilde{z}^{-1}\right) \\ &= \tilde{z}\left[\tilde{z} - \frac{D(s)}{N(s)}\right]D(-s) + N(-s)\left[\frac{D(s)}{N(s)}\right] = 0.\end{aligned} \tag{27}$$

Hence, it implies that

$$\begin{aligned}\tilde{\Delta}_\delta(s, z, \tilde{z}) = \tilde{z}^2 N(s)D(-s) - \tilde{z}D(s)D(-s) \\ + N(-s)D(s) = 0.\end{aligned} \tag{28}$$

From there, it yields

$$\frac{N(s)}{D(s)}\tilde{z}^2 - \tilde{z} + \frac{N(-s)}{D(-s)} = 0, \tag{29}$$

For $s = j\omega$ and $\tilde{z} = e^{-j\omega\tilde{T}}$, the roots of (29) must lie in the left-hand side of the S-plane. Substituting $\tilde{z} = e^{-j\omega\tilde{T}}$ and $s = j\omega$ into (29) gives

$$\frac{N(j\omega)}{D(j\omega)}e^{-2j\omega\tilde{T}} - e^{-j\omega\tilde{T}} + \frac{N(-j\omega)}{D(-j\omega)} = 0, \tag{30}$$

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

$$e^{-j\omega\tilde{T}}\left[\frac{N(j\omega)}{D(j\omega)}e^{-j\omega\tilde{T}} - 1 + \frac{N(-j\omega)}{D(-j\omega)}e^{j\omega\tilde{T}}\right] = 0, \tag{31}$$

which gives

$$\frac{N(j\omega)}{D(j\omega)}e^{-j\omega\tilde{T}} + \frac{N(-j\omega)}{D(-j\omega)}e^{j\omega\tilde{T}} = 1, \tag{32}$$

and in polar form

$$\begin{aligned}\frac{N(j\omega)}{D(j\omega)}\left[\cos\omega\tilde{T} - j\sin\omega\tilde{T}\right] + \\ \frac{N(-j\omega)}{D(-j\omega)}\left[\cos\omega\tilde{T} + j\sin\omega\tilde{T}\right] = 1.\end{aligned} \tag{33}$$

Noting that in polar form the magnitude is an even function while the phase is an odd function, it yields

$$2\left|\frac{N(j\omega)}{D(j\omega)}\right|\cos\left(\omega\tilde{T}+\angle\frac{N(j\omega)}{D(j\omega)}\right)=1. \quad (34)$$

Hence, if the following condition is satisfied for all frequencies, then the characteristic equation of the closed-loop transfer function in (18) will not have any roots with positive value for real parts, which yields a stable system independent of the value of $\tilde{T}$:

$$\left|N(j\omega)\big/D(j\omega)\right|<\frac{1}{2}, \quad \forall\omega. \quad (35)$$

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Remark 2: Based on remark 1, In order to increase the robustness of the overall system against uncertainties in the time delay, one can design the local controller such that Eq. (35) is always valid. However, it should be noted that there is a trade off between $\left|N(j\omega)/D(j\omega)\right|$ and the precision of the transparency. The following theorem relaxes further this condition. In other words, transparency of the overall system can be improved without compromising stability of the system, if the time delay is communication channel is small enough.

First, *small* time delay must be defined for teleoperation systems. Brooks [15] proposed a bandwidth between 4 and 10 Hz for teleoperation systems. Consequently, by using the following first-order approximation for the time delay in Laplace transform

$$e^{-sT}=1-sT \quad (36)$$

and also noting that $\left|e^{-T(j\omega)}\right|=\left|1-T(j\omega)\right|=\sqrt{1+T^2\omega^2}\cong 1$, we may select T=0.001 sec. Therefore, when it is referred to small time delay in communication channel, it means a time delay approximately equal to 0.001 sec.

Proposition: The time delay in communication channel in teleoperation systems is considered small for $T<0.001$ sec. This proposition is based on the suggested bandwidth between 4 and 10 by Brooks [15], and using the first order approximation of e^{-sT} as $1-sT$.

***Theorem 3*:** Let $\delta=\tilde{T}-T$ denote the estimation error for the time delay. Then, the proposed control system, shown in Fig. 6, is stable for small time delays if

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

where $D(s)$ and $N(s)$ have are given in (19) and (20), respectively, $D(s)$ is Hurwitz, and

$$\deg\left(D(s)\right)>\deg\left(N(s)\right).$$

Proof: Using the first-order approximation of e^{-Ts} and $e^{-\tilde{T}s}$ as

$$e^{-sT}=1-sT \quad , \quad e^{-s\tilde{T}}=1-s\tilde{T}. \quad (37)$$

And substituting these equations into the characteristic equation of the control system (16) yields

$$\begin{aligned}\Delta_\delta(s)&=1+C_m(s)G(s)+C_m(s)G(s)(e^{-sT}-e^{-s\tilde{T}})\\&=1+C_m(s)G(s)+C_m(s)G(s)(1-sT-1+s\tilde{T})\\&=1+C_m(s)G(s)[1-s(T-\tilde{T})]\\&=1+C_m(s)G(s)\,e^{-s(T-\tilde{T})}.\end{aligned} \quad (38)$$

Substituting $G(s)=N_g(s)/D_g(s)$ and $C_m(s)=N_c(s)/D_c(s)$ into (38) gives

$$\begin{aligned}\Delta_\delta(s)&=1+C_m(s)G(s)e^{-s(\tilde{T}-T)}\\&=D(s)+N(s)e^{-s(T-\tilde{T})}.\end{aligned} \quad (39)$$

Using (38) and (39) and $\delta=\tilde{T}-T$, Eq. (16) can be rewritten as

$$M_\delta(s)=\frac{N(s)e^{-s\delta}}{D(s)+N(s)e^{-s\delta}}\,e^{-s(T-\delta)}, \quad (40)$$

Since $e^{-s(T-\delta)}$ doesn't play any role in stability of the closed-loop system, according to the Tsypkin theorem [16], the condition for closed-loop stability is

$$\left|N(s)\big/D(s)\right|_{s=j\omega}<1, \quad \forall\omega. \quad (41)$$

o

Remark 3: It should be noted that the condition given in (41) for small time delays doesn't have any conflict with the results of theorem 2, given in (35). In other words, if condition (35) is satisfied, then (41) is guaranteed as well. This is because in the proof of theorem 3, the time delay was assumed to be small, which imposes more restriction on the time delay but less restriction on the design of the local controllers.

5. Simulations

In order to evaluate the effectiveness of the proposed control method, the controller has been applied to the following example, which has been used in literatures [12]. In this example, the dynamics of the master and slave systems are described as a 1-DOF mass-damper system by

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

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 from the environment. The system parameters are set to M_m = 0.4 kg and B_m = 3 N/m for the master, M_s = 1 kg and B_s = 0.2 N/m for the slave, and Z_e =1 for the environment impedance. In simulations, two different conventional controllers are designed. The first one is a PD controller, called the remote controller, which is used for the slave controller C_s . The second controller is a PD controller, called the local controller, which is used for the master controller C_m.

The remote controller is designed such that $\hat{G}(s)$ in (2) is stable and the local controller is designed such that the behavior of the closed-loop teleoperation system is acceptable (i.e. stability of the overall closed-loop and force tracking is guaranteed). Furthermore, using these controllers, the stability conditions of the closed-loop system in (7), (35) and (41) must hold. These conditions can be checked graphically with Bode plots as well.

In order to demonstrate performance of the proposed method against time delays with perturbations, simulations are performed for two general cases: 1) possibly stability (Section 4.1) and 2) intrinsically stability (Section 4.2). In addition, two different inputs are used in simulations; step input and sinusoidal input.

5.1. Possibly Stability

Table 1 presents the type of controllers and their typical coefficients for possibly stability. Notice that, these values are not unique and are selected only to satisfy the stability condition given in Section 4.1. The simulation results are shown in Figs. 9-12. These figures are the time delay, the Bode plot for presenting the stability condition (7), and transparency response for the step and sinusoidal inputs, respectively. As these figures show, the proposed structure exhibits good performance. The dashed line in Fig. 10 represents the right hand side of Eq. (7), which must be preserved in the control design.

5.2. Intrinsically Stability

Simulations for the intrinsically stability case are carried out for different values of time delay. In case I, the time delay is small with some perturbations. In case II, the time delay is relatively large with considerable perturbations. In these cases, normally distributed random signals are used as perturbed time delay. Moreover, the time delay is estimated with an FIR filter [17]. Order of the FIR filter has been chosen as $P = 6$, because for $P \geq 6$ the estimation error of the time delay will be very small and negligible [17]. Tables 2 and 3 show the type of controllers and their typical coefficients used in simulations. Notice that, these values are not unique and have been selected only to satisfy the stability conditions given in (35) and (41) for large and small time delays, respectively.

Figs. 13 and 17 show the time delays in communication channel for cases I and II. The stability conditions can be checked using the Bode plot given in Figs 14 and 18. The dashed lines in Figs. 14 and 18 represent the right hand side of (41) and (35), which are $20\log(1) = 0$ db and $20\log(0.5) \cong -6$ db, respectively. Figs. 15 and 16 show the step and sinusoidal response of the teleoperation system for the small time delays, while Figs. 19 and 20 show the same responses for the large time delays.

Fig. 21 presents an unstable teleoperation system for small and perturbed time delay, when the stability condition in (41) does not hold.

6. Conclusions

A simple control method for teleoperation systems was proposed in this paper. The proposed method provides transparency and stability with robustness against uncertainties in the time delay in communication channel. Two local controllers, one for the master side and the other one for the slave side, was design. The slave controller guarantees the position tracking while the master controller guarantees the force tracking as well as stability of the closed-loop system. The major advantage of the proposed method is that one can use the classical control methods to design local controllers. Furthermore, stability of the teleoperation systems can be checked graphically with the Bode plot method. Therefore, the controller design would be simple and straightforward. In simulations, by using two PD controllers, for a 1-DOF telemanipulation system, it was shown that the proposed method is a viable selection for teleoperation systems with perturbed time delay in communication channel. Future works in this area will include mismatch model in the teleoperation systems and conditions for stability of such a case.

References

[1] Melchiorri, C., and Eusebi, A., 1996, "Telemanipulation: System aspects and control issue," *Proceedings of Modeling and Control of Mechanisms and Robots*, World Scientific, Singapore, pp. 149-183.

[2] Lawrence, D. A., 1993, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robot. Automat*., 9 (5), pp. 625-637.

[3] Ryu, J. H. and Kim, J. H., 2005, "Stable and high performance telerobotic with time domain passivity control: reference energy following scheme," *IEEE Conference on Control Applications*., pp. 782-787, 2005.

[4] Ching, H. and Book, W. J., 2006, "Internet-based bilateral teleoperation based on wave variable with adaptive predictor and direct drift control," *J. Dyn. Syst., Meas. Contr*., 128 (1), pp. 86-9.

[5] Kim W. S, Hannaford. B., and Bejczy A. K., 1992, "Force reflection and shared compliant control in operating telemanipulators with time delay," *IEEE Trans. Robot. Automat*., 8, pp. 176-185.

[6] Zhu, W. H., and Salcudean, S. E., 2000, "Stability guaranteed teleoperation: an adaptive motion/force control approach," *IEEE Trans. Automat. Cont*., 45 (11), pp. 1951-1969.

[7] Alfi, A., and Farrokhi, M., 2006, "Bilateral transparent telerobotic with long time-varying delay: new control design and stability analysis," *Proceedings of CDC 2006*, San Diego, USA.

[8] Alfi, A., and Farrokhi, M., 2006, "Bilateral control to achieve transparent telerobotic with perturbation of static time delay," *Proceedings of IEEE IECON 2006*, Paris, France.

[9] Alfi, A., and Farrokhi, M., 2006, "On the closed-loop stability analysis of transparent telerobotic systems with time-varying delay using a new structure," *Proceedings of IFAC WTDS 2006*, L'Aquila, Italy.

[10] Arcara, P., and Melchiorri, C., 2002, "Control schemes for telerobotic with time delay: A comparative study," *Robot. Autonomous Syst*., 38, pp. 49-64.

[11] Gu, K., Kharitanov, V. L., and Chen, J., 2003, *Stability of Time-Delay Systems*, Birkhauser, Stuttgart.

[12] Valdovinos, L. G., Parra-Vega, V., and Arteaga., M., A., 2007, "Observer-based sliding mode impedance control of bilateral teleoperation under constant unknown time delay," *Robot. Autonomous Syst*., 55, pp. 609-617.

[13] Marquez, H. J., 2003, *Nonlinear Control Systems: Analysis and Design*, Wiley-Inter Science

[14] Yamanaka, K. and Shimemura, E., 1987, "Effects of mismatched Smith controller on stability systems with time-delay," *Automatica*, 23 (6), pp. 787-791.

[15] Brooks, T. L., 1990, "Teleoperator system response for nuclear telepresence," STX Publication, ST System Corp.

[16] Niculescu, S. I., 2001, *Delay Effects on Stability: a Robust Control Approach*, Springer Verlarg, Heidelberg

[17] Balestrino, A., Verona, F. B, and Landi, A., 1998, "Online process estimation by ANNs and Smith controller design," *IEE. Proceedings on Control Theory and Application*, 145 (2), pp. 231-235.

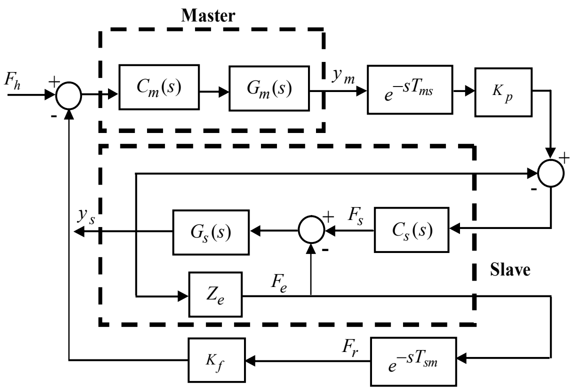


Fig. 1 The proposed control scheme (the first form)

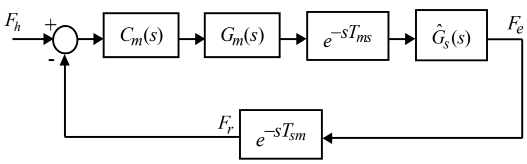


Fig. 2 The second form of the proposed control scheme

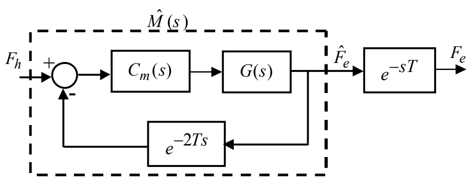


Fig. 3 Equivalent control structure for Fig. 2

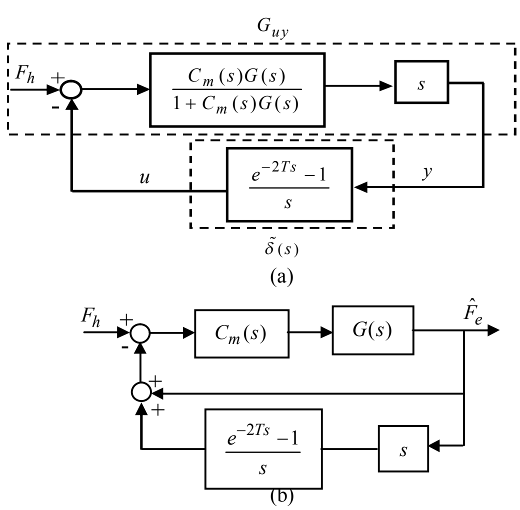


Fig. 4 The equivalent structure of $\hat{M}(s)$ in Fig. 3

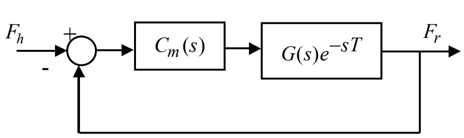


Fig. 5 New control scheme (the third form)

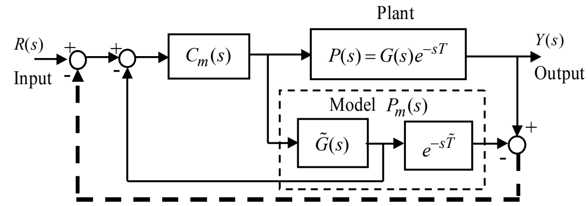


Fig. 6 The Smith predictor control method

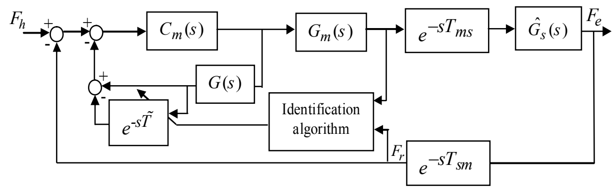


Fig. 7 Structure of the master controller

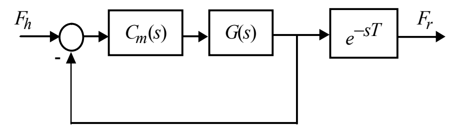


Fig. 8 The desired control-loop configuration

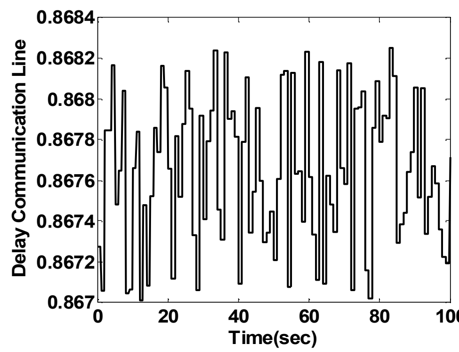


Fig. 9 Time delay in communication channel

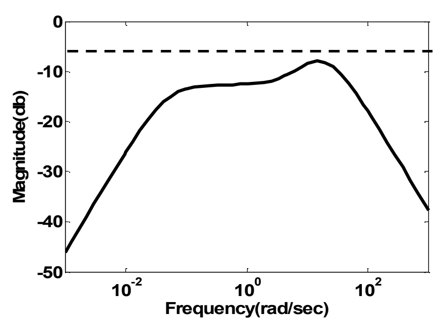


Fig. 10 Bode plot for presenting stability condition (7)

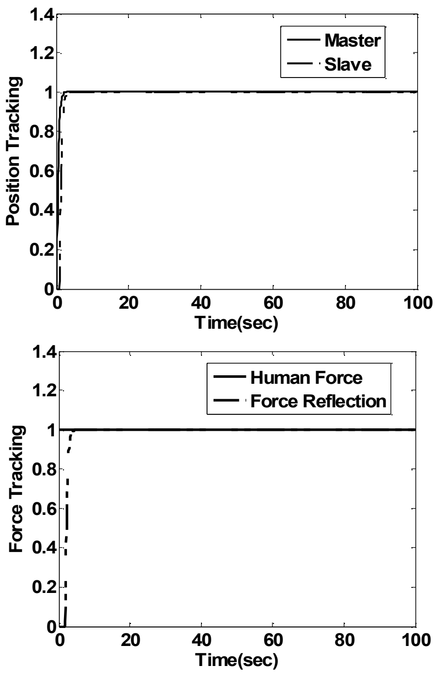


Fig. 11 Transparency response for step input.

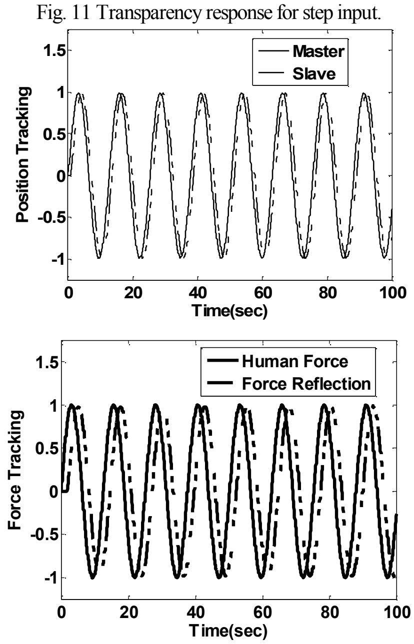


Fig. 12 Transparency response for sinusoidal input

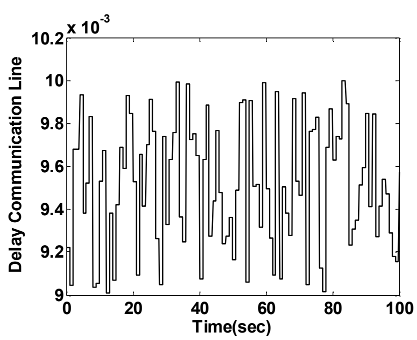


Fig. 13 Time delay in communication channel (case I)

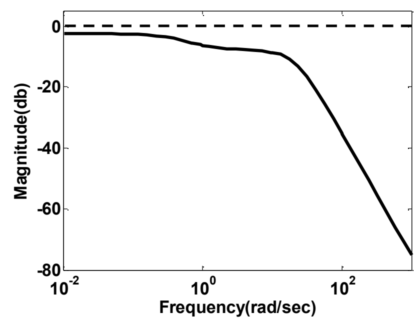


Fig. 14 Bode plot for presenting stability condition (41) (case I)

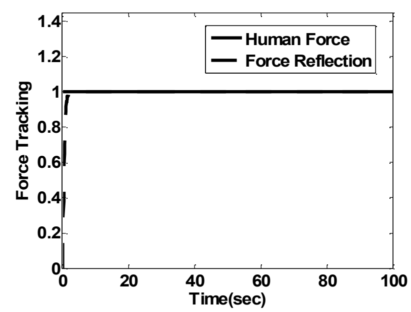


Fig. 15 Transparency response for step input (case I)

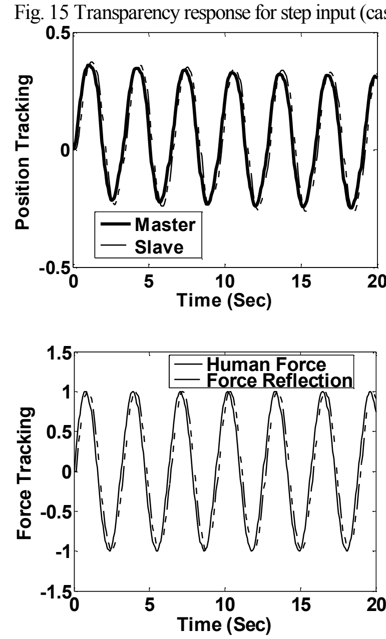


Fig. 16 Transparency response for sinusoidal input (case I).

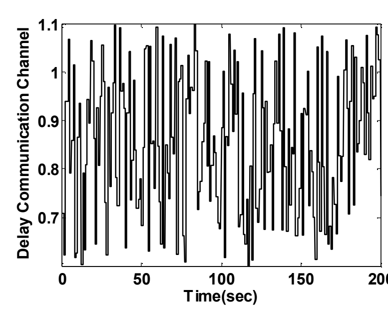


Fig. 17 Time delay in communication channel (case II)

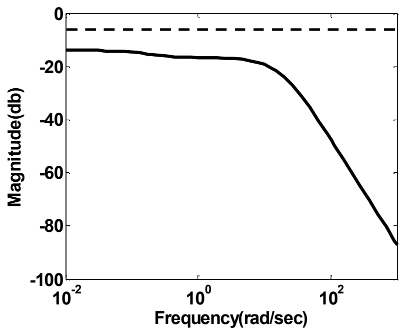


Fig. 18 Bode plot for presenting stability condition (35), (case II)

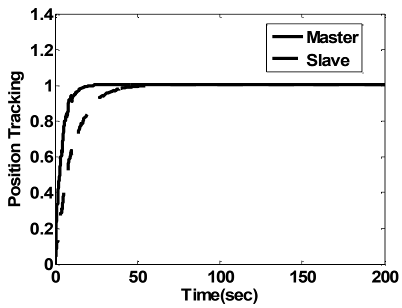


Fig. 19 Transparency response for step input (case II).

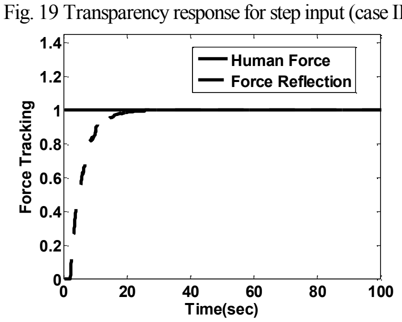


Fig. 19 Transparency response for step input (case II).

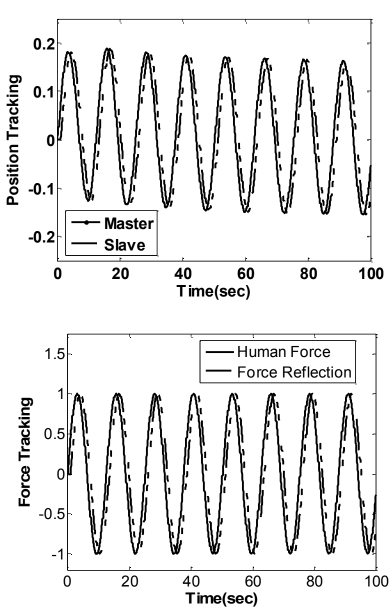
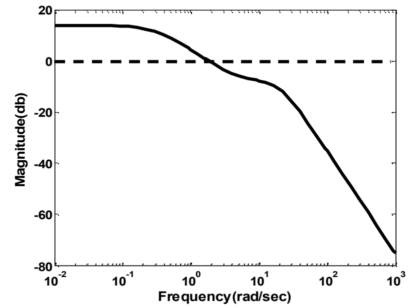
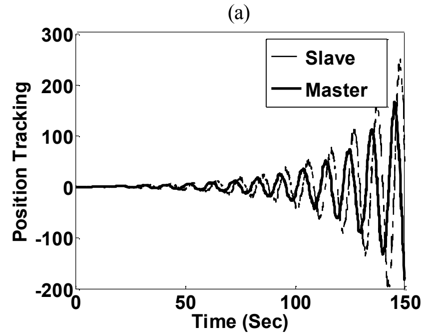


Fig. 20 Transparency response for sinusoidal input (case II)



(a)



(b)

Fig. 21 Unstable teleoperation system for small time delay in communication channel when stability condition in (41) does not hold, (a) Bode plot, (b) the step response.

Table 1 The type of controllers and their parameters for possibly stability

Controller	Type	K_P	K_D
Local (Master)	PD	0.75	0.15
Remote (Slave)	PD	20	34.8

Table 2 Type of local (Master) controllers

Case	Local Controller	K_P	K_D
Case I	PD	0.1	0.5
Case II	PD	0.65	0.85

Table 3 Type of remote (Slave) controllers

Case	Remote Controller	K_P	K_D
Case I	PD	20	34.8
Case II	PD	20	34.8