Robust Bilateral Teleoperation with Varying Time Delay

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Abstract: *In this paper a novel structure design to control teleoperation systems, with variable communication time delay is presented. Transparency is used as an index to evaluate the performance of the closed-loop system. The focus in this paper is to achieve the transparency for bilateral teleoperation in presence of variable time delay in communication channel. For this reason, two local controllers for bilateral teleoperation systems, by using compliance control and direct force-measurement force-reflection control, have been designed. The proposed controllers make the slave manipulator follow the master in spite of the variable time delay in communication channel. The advantage of the proposed method is that one can use the classical or advanced control methods together or alone for designing local controllers. Simulation results show very promising performance of the controllers.*

Keywords: Bilateral Teleoperation, Time delay, Transparency

1 Introduction

The remote control of telerobotic manipulators has gained considerable attention in recent years. Teleoperated mobile robots are widely used in order to carry out complex 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 the seas and sea beds [1]. A teleoperated system consists of five different parts, as shown in Figure 1: master robot, communication channel, slave robot, 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 can be fedback 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 time delay in communication channel appears that can not be ignored. This time delay can destabilize the bilateral teleoperation system [3], [4]. To solve this problem, different control schemes have been proposed in literature. The most widely used control schemes are the passivity theory [5], compliance control [6], wave variables [7] and adaptive control [8]. In each method, transparency is a major criterion for performance of telerobotic systems in presence of time delay in communication channel. If the slave accurately reproduces the master's commands and the master correctly feels the slave forces, the human operator experiences the same interaction as the slave would. This is called complete transparency in teleoperation system.

In this paper a novel control method of bilateral teleoperation systems with variable time delay in communication channel and complete transparency is proposed. To achieve transparency, Compliance control and direct force-measurement force-reflecting control method have been used.

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. Section 5 shows the simulation results. And finally, section 6 draws conclusions and presents the future work.

Figure 1: The General Structure of a Bilateral Teleoperation System

2 General Teleoperation 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 2, the teleoperation system is modelled 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 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 [9]

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

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

$$F_e = Z_e V_s \qquad (2)$$

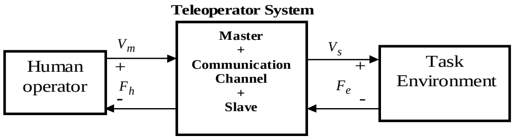

Figure 2: Two-Part Model of Teleoperation Systems

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". Using the scaling factors, the velocity /position command to the slave and the force command to the master are modified such that

$$V_m = K_p V_s \qquad (3)$$

$$F_h = K_f\ F_e \qquad (4)$$

where K_p and K_f are the position and force scaling factors, respectively. Then, for ideal one-degree-of-freedom teleoperation system, the **H** matrix is

$$\mathbf{H}_{\text{ideal}} = \begin{bmatrix} 0 & K_f \\ -K_p & 0 \end{bmatrix} \qquad (5)$$

3 The Proposed Control Scheme

The proposed control scheme for teleoperation systems, in presence of varying time delay in communication channels, as shown in Figure 3, where 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 our proposed method, we combined the compliance control and direct-force measurement-force reflecting control. In Compliance control scheme, Force measurements are used at the slave site and a Compliance term C_c is inserted in the slave local controller. Direct-force measurement-force reflecting control is one simple form of a force reflecting scheme using a force sensor. 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 slave has to follow the position/velocity, and the local controller guarantees the force tracking. Furthermore, the local controller guarantees the stability of the overall system. Here we assume that k_p and k_f are equal to one and f_e is measurable. In next sections, the design of local controllers will be described.

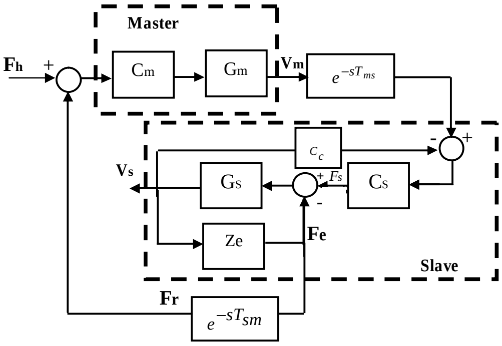

Figure 3: Proposed Control Scheme (First Form)

4 Design of Control Schemes

4.1 Local Slave Controller

Based on compliance control, we propose the local slave controller. If it is assumed that the output of master and slave robot is velocity, then from figure 3, the transfer function of the slave to the master can be written as

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

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 for linear systems like PD (Proportional plus Derivative), PI (Proportional plus Integral) and PID (Proportional plus Integral plus Derivative), to design a local slave controller C_s for the remote site such that system in (6) is stable. So, the position of the slave robot will follow the position of the master robot in such a way that the tracking error for position is satisfactory. In this paper we use a PI controller as the local slave controller.

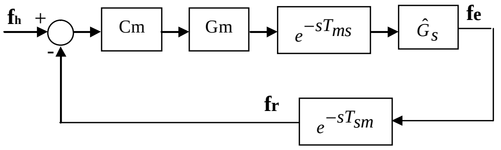

Figure 4: New Control Scheme (Second Form)

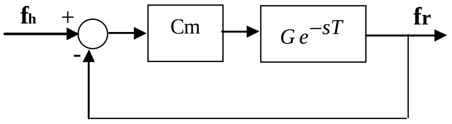

Figure 5: New Control Scheme (Third Form)

4.2 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:

$$\hat{G}_s(s)=\frac{Z_eC_s(s)G_s(s)}{1+Z_eG_s(s)+C_cC_s(s)G_s(s)} \qquad (7)$$

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

$$T=T_{ms}+T_{sm} \qquad (9)$$

$$F_r(s)=F_e(s)e^{-sT} \qquad (10)$$

Using these variables, the control scheme, shown in Figure 3, can be simplified as Figure 4. We 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.) 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 4. Let's define this new output as F_r. So, the system shown in Figure 4 can be represented as the system in Figure 5. From Figure 5, the transfer function of the overall closed-loop system can be written as

$$M(s)=\frac{C_m(s)G(s)e^{-Ts}}{1+C_m(s)G(s)e^{-Ts}} \qquad (11)$$

Notice that the roles of M(s) are the stability of the overall system and force tracking. From (11), it can be seen that delay has been contained in the denominator of the closed-loop transfer function and then, delay 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 [10]. This predictor can effectively cancel out time delays from the denominator in the transfer function of the closed-loop system. Figure 6 shows the general structure of a Smith predictor.

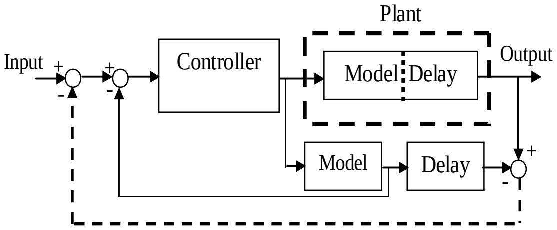

Figure 6: The Complete Smith Predictor Control Scheme

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.

Now, as it is well known, it is hard to get the precise model of a teleoperation system. Moreover, the system parameters usually changes with time. This will lead to some differences between the predictive model and the practical plant, which is called mismatched model. In addition to that, the time delay, which is relatively large and cannot be ignored, is not constant.

In order to compensate the mismatched model, a second feedback loop can be introduced in the closed-loop system (dashed line in Figure 6). In this paper, in order to completely compensation the effect of time delay and changes in the system parameters, the variable time delay will be estimated. Notice that although second feedback loop (shown by dashed line in Figure 6) compensates the model parameter variation in a dynamic model, which is combined of master and slave, but the variations in the model, parameters must be bounded [11]. Take into consideration the model parameter variation in a dynamic model of combined master and slave system will be investigation in future work.

In order to improve the control performance, we use an adaptive controller, which can cope with the changes in the system parameters and also can handle varying time delay. A fuzzy controller seems to be a good choice for this reason (Figure 7).

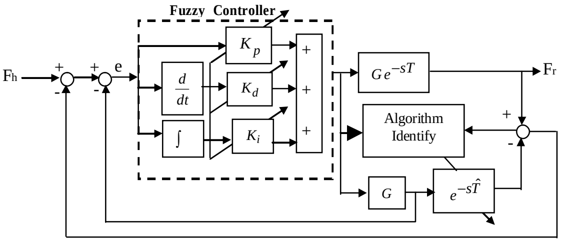

Figure 7: Structure of Local Master Controller

5 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. Several estimation methods for time delay may be broadly classified into time domain and frequency domain techniques; theses techniques can be performed online or offline [12]. Different methods for time-varying parameter estimation have been proposed in the literature. One of the most effective and widely used methods is the Recursive Least square (RLS) [13]. In this paper, we have employed the improved least squares method with covariance modification for estimation of time delay in communication channel as follows [14]:

$$\mathbf{P}(k) = \mathbf{P}(k-1) - \frac{\mathbf{P}(k-1)\boldsymbol{\varphi}(k-1)\boldsymbol{\varphi}^T(k-1)\mathbf{p}(k-1)}{r + \boldsymbol{\varphi}^T(k-1)\mathbf{p}(k-1)\boldsymbol{\varphi}(k-1)} \tag{12}$$

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \frac{\mathbf{P}(k-1)\boldsymbol{\varphi}(k-1)}{r + \boldsymbol{\varphi}^T(k-1)\mathbf{P}(k-1)\boldsymbol{\varphi}(k-1)} \tag{13}$$

$$\times[y(k) - \boldsymbol{\varphi}(k-1)^T\hat{\boldsymbol{\theta}}(k-1)]$$

where $0 < r \leq 1$. Suppose the initial values are $\mathbf{P}(0) = s^2\mathbf{I}$ and $\hat{\boldsymbol{\theta}}(0) = 0$, where s^2 is a sufficiently large number, and $\mathbf{I}$ is an identity matrix. Now, let's write the model of the system as

$$\mathbf{y}(t) = \boldsymbol{\varphi}^T(t)\boldsymbol{\theta}(k) \tag{14}$$

where $\boldsymbol{\theta}$ and $\boldsymbol{\varphi}$ are vectors of inputs and free-parameter weights of the model, respectively. Parameter vector $\boldsymbol{\theta}$ was identified on-line by the least squares method and the system output is the estimated time delay at time step $(k+1)$.

6 Modeling of Teleoperation Systems

6.1 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 robotic manipulators with several degrees of freedom (DOF). The dynamic Model of an n DOF robotic manipulator is usually given as [15]

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{F}(\mathbf{q},\dot{\mathbf{q}}) \tag{15}$$

where $\boldsymbol{\tau} \in \Re^{n\times 1}$ is the torque 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 single DOF with linear equations for the dynamics of the remote robot manipulator. Taking the interaction with the environment into account, yields

$$t - t_e = M_s\ddot{q} + F_s\dot{q} \tag{16}$$

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

6.2 Master Model

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

$$J_m\ddot{q} + b_m\dot{q} = t_m \tag{17}$$

where J_m and b_m are the manipulators inertia and damping coefficient. The force t_m applied to the Manipulator depends on the interaction with the human operator.

7 Simulations

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

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

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

where B is the viscose friction coefficient, M is the manipulators inertia, x is the position and F is the input force; Indices m and s are for the master and the slave systems, respectively; F_h is the force applied to the master by human operator and F_e is the force exerted on the slave by its environment.The numeric values of the simulation parameters are in table I. Simulations have been executed for two different controllers. The first is a conventional PI and PID controller, called classical controller, which have been used for the local slave and master controllers, respectively. The second is a PI and PID Fuzzy controller, called combinational controller, which have been used for the local slave and master controllers, respectively. For classical controllers, the best choices are: 1) for the slave: $K_p = 9.8$ and $K_I = 30$. 2) for the master controller: $K_p = 0.1$, $K_d = 0.1$, $K_I = 0.5$. Notice that the PI controller is designed such that $\hat{G}(s)$ is stable and the PID controller is design such that behavior of teleoperation systems is admissible. Furthermore, In order to modify the desired displacement received from he master side accordingly to the interaction with the environment, a compliance term Cc=1 is chosen. For fuzzy controllers we used three inputs: the error, derivative of the error, and integral of the error. Figures 8 and 9 show the membership functions for the input error e, change of the input error Δe, and integral of the input error, Σe and the membership function for the output variable, respectively. These membership functions have been obtained by acquiring knowledge from the system behavior. The abbreviations nb, nm, ns, ze, ps, pm, and pb stand for negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. Furthermore, The rule-base of computing output is shown in Figure 10. The mamdani's min-max fuzzy inference engine and the center of average defuzzifier have been employed in simulations [16-17]. To produce variable time delay, a normally distributed random signal with Mean=1 and variance=2 have been used (Figure 11). Figure 12 shows the force tracking and the position tracking for classical and combinational controllers. As these Figures show, the proposed method has effectively controlled the system, in order to achieve transparency and stability of teleoperation system in presence of variable time delay in communication channel. Also, the difference between the classical controllers and the combinational controllers, in terms of transient responses, is obvious.

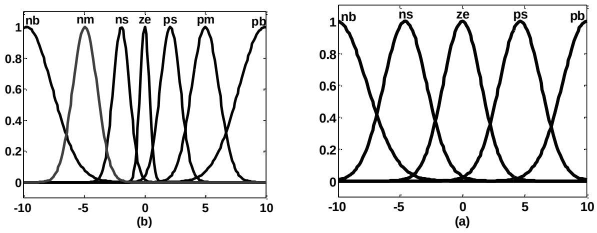

Figure 8: Membership functions for the linguistic input variables (a) Error e (b) Difference Δe and Sum Σe of the Tracking Error

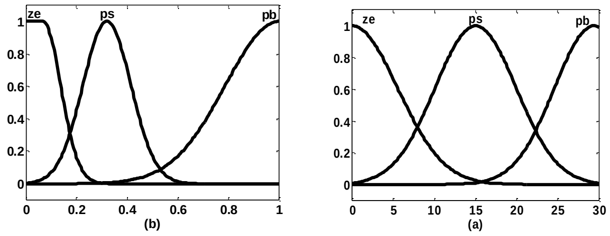

Figure 9: Membership functions for the linguistic output variables (a)K_p and K_i (b) K_d

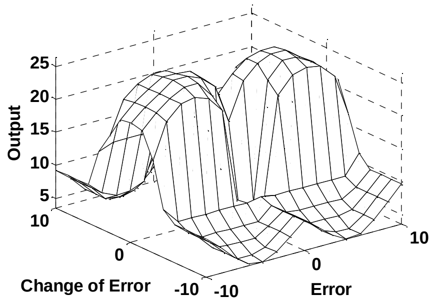

Figure 10: Fuzzy Control Rules

Table 1: 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 of master
B_s =0.2 N/m	Linear friction of of slave
$Z_e = 1$	Environment Impedance

Conclusion

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

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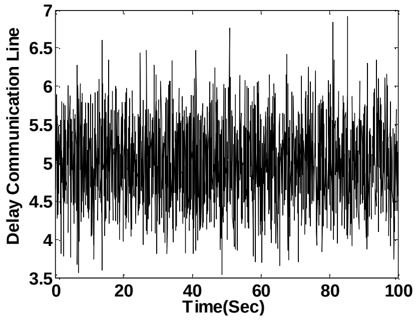
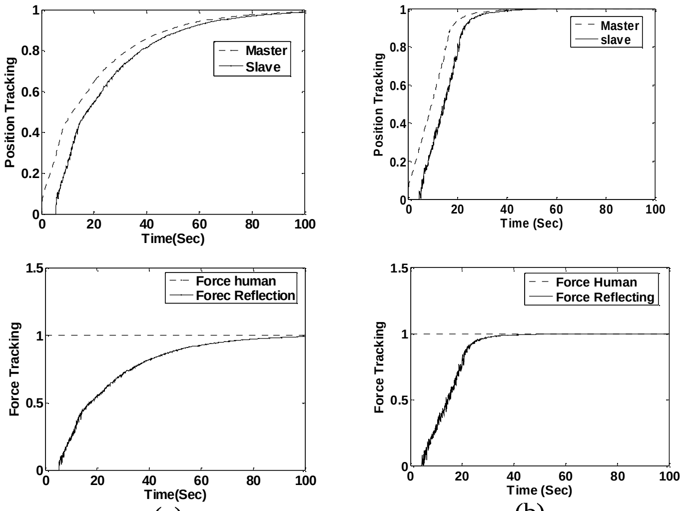


Figure 11: Time Delay in Communication Channel



(a) (b)

Figure 12: Transparency Response
(a) Classical Controller (b) Combinational Controller