Joint 48th IEEE Conference on Decision and Control and
28th Chinese Control Conference
Shanghai, P.R. China, December 16-18, 2009

Bilateral Control with Constant Feedback Gains for Teleoperation with Time Varying Delay

Toru Namerikawa

Abstract— **This paper describes a bilateral control of nonlinear teleoperation with time varying communication delay.**

The proposed method are simple PD-type controllers which are independent of the rate of time delay change and depend on the upper bound of round-trip delay. The proposed control strategy is independent of parameter uncertainties of the model of the robots and the operator and remote environment. The delay-dependent stability of the origin is shown via Lyapunov stability theorem. Furthermore the proposed strategy also achieves master-slave position coordination and bilateral static force reflection.

Several experimental results with wireless communication and the Internet show the effectiveness of our proposed strategy.

I. Introduction

Teleoperation is the extension of a person's sensing and manipulation capability to a remote location and it has been tackled by researchers in control theory and robotics over the last few decades. A teleoperator is a dual robot system in which a remote slave robot tracks the motion of a master robot, which is, in turn, commanded by a human operator. To improve the task performance, information about the remote environment is needed. In particular, force feedback from the slave to the master, representing contact information, provides a more extensive sense of telepresence. When this is done, the teleoperator is said to be controlled bilaterally [1].

In bilateral teleoperation, the master and the slave are coupled via a communication network, and time delay is incurred in transmission of data between the master and slave site. It is well known that the delay in a closed-loop system can destabilize an otherwise stable system. Recently, essential research interest has been attracted by using the Internet as a communication network for teleoperation [2], [3], [4], [5], [6]. Using the Internet for communication network provides obvious benefits in terms of low cost and availability. However, at the present time, for teleoperation over the Internet the delays vary with such factors as congestion, bandwidth, or distance, and these varying delays may severely degrade performance or even result in an unstable system. Stabilization for a teleoperation with constant communication delays has been achieved by the scattering transformation based on the idea of passivity [7] (This is equivalent wave variable formulation [8]). Then, an additional structure with position feedforward/feedback controls has been proposed to improve the position coordination and force reflection performance [9], [10]. In [11] and [12], a PD-type controller without scattering transformation has been proposed stabilizing for the constant communication delays. In these methods, the position coordination and force reflection have also been achieved by explicit position feedback/feedforward control. In [7]- [12], however, the time varying communication delays have not been treated.

Several researchers addressed a problem of the teleoperation with time varying delays and several control methods based on scattering transformation have been reported. Some preliminary results are contained in [2], [3], and interesting epoch-making result has been obtained in [4]. In [4], a simple modification to the scattering transformation has been proposed, here a time varying gain was inserted into the communication block which guarantees passivity for arbitrary time varying delays provided a bound on the rate of change of the time delays. In [2]-[4], however, it is insufficient for the performance of force reflection and positional coordination due to the lack of the explicit position feedback/feedforward controls. In [5] and [6], they have proposed control methods without the scattering transformation. However, there are problems in which the controllers require the model of the robots, the environment, the human operator and the communication. Then robustness for parameter uncertainties has not been guaranteed and the controllers have become complex. In [16], we addressed a problem of nonlinear teleoperation with time varying communication delays. The proposed strategies were a couple of simple PD-type controllers extending [11] and [12]. Using Lyapunov-Krasovskii function, the delay-dependent stability of the origin was shown.

However the stability condition of the teleoperation system with time varying delay depended on the rate of time delay change and the previous works utilized the time varying feedback gains dependent on the time delay[4], [5], [16]. This is actually not practical in real-time control.

Hence we propose a novel bilateral control strategy for nonlinear teleoperation with time varying communication delay.

The proposed method are simple PD-type controllers which are independent of the rate of time delay change and depend on the upper bound of round-trip delay. The controller consists of D-controls independent of on the rate of change of delay and P-controls dependent to the upper bound of round-trip delay. The proposed control strategies are independent of parameter uncertainties of the model of the robots, the human operator and the remote environment.

The delay-dependent stability of the origin is shown via Lyapunov stability Theorem. Furthermore the proposed

T. Namerikawa is with Department of System Design Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522 JAPAN
namerikawa@sd.keio.ac.jp

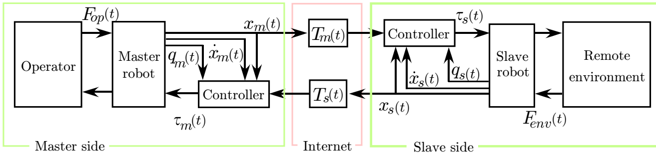

Fig. 1. Teleoperation System

strategy also achieves master-slave position coordination and bilateral static force reflection.

Several experimental results with wireless communication and the Internet show the effectiveness of the proposed strategy.

II. Dynamics of Teleoperation System

In this paper, we consider a pair of robotic systems coupled via communication lines as Internet with time varying delays as shown in Fig.1.

Assuming absence of friction and other disturbances, the master and slave robot dynamics with n-DOF are described as [14]

$$\begin{cases} M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + g_m(q_m) = \tau_m + J_m{}^T F_{op} \\ M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + g_s(q_s) = \tau_s - J_s{}^T F_{env} \end{cases} \tag{1}$$

where the subscript "m" and "s" denote the master and the slave indexes,

q_i $(i=m,s) \in \mathscr{R}^{n\times 1}$ are the joint angle vectors, τ_i $(i=m,s) \in \mathscr{R}^{n\times 1}$ are the input torque vectors, $F_{op} \in \mathscr{R}^{n\times 1}$ is the operational force vectors applied to the master by human operator, $F_{env} \in \mathscr{R}^{n\times 1}$ is the environmental force vectors applied to the environment by the slave, $M_i(q_i)$ $(i=m,s) \in \mathscr{R}^{n\times n}$ are the symmetric and positive definite inertia matrices, $C_i(q_i,\dot{q}_i)\dot{q}_i$ $(i=m,s) \in \mathscr{R}^{n\times 1}$ are the centrifugal and Coriolis torque vectors, $g_i(q_i)$ $(i=m,s) \in \mathscr{R}^{n\times 1}$ are the gravity terms, and $J_i(q_i)$ $(i=m,s) \in \mathscr{R}^{n\times n}$ are Jacobian, respectively.

Here the following assumption for the Jacobian matrix $J_i(i=m,s)$ is introduced.

Assumption 1: The Jacobian matrix J_i $(i=m,s)$ should be nonsingular.

It is also well known that the joint angles q_i $(i=m,s)$ and the position x_i $(i=m,s)$ in task coordinate can be transformed under the Assumption 1 as

$$\begin{aligned} x_i &= f_i(q_i) \quad (f_i \textit{ is an adequate function}) && (2)\\ \dot{x}_i &= J_i\dot{q}_i && (3)\\ \ddot{x}_i &= J_i\ddot{q}_i + \dot{J}_i\dot{q}_i \qquad (i=m,s) && (4) \end{aligned}$$

These equations transform the dynamics (1) in the joint space into one in the task coordinate. The indices : $(q_i),(q_i,\dot{q}_i)$ are omitted in the following.

$$\begin{aligned} M_{em} &= J_m^{-T} M_m J_m^{-1} && (5)\\ M_{es} &= J_s^{-T} M_s J_s^{-1} && (6)\\ C_{em} &= J_m^{-T}(C_m - M_m J_m^{-1}\dot{J}_m)J_m^{-1} && (7)\\ C_{es} &= J_s^{-T}(C_s - M_s J_s^{-1}\dot{J}_s)J_s^{-1} && (8)\\ g_{em} &= J_m^{-T} g_m && (9)\\ g_{es} &= J_s^{-T} g_s && (10) \end{aligned}$$

The master and slave robot dynamics in the task space are given as

$$\begin{cases} M_{em}\ddot{x}_m + C_{em}\dot{x}_m + g_{em} = J_m^{-T}\tau_m + F_{op} \\ M_{es}\ddot{x}_s + C_{es}\dot{x}_s + g_{es} = J_s^{-T}\tau_s - F_{env} \end{cases} \tag{11}$$

It is well known that the dynamics (1) have several fundamental properties as follows [14].

Property 1: M_{ei} $(i=m,s)$ are are symmetric and positive definite.

Property 2: $N_{ei} = \dot{M}_{ei} - 2C_{ei}$ $(i=m,s)$ are skew symmetric.

Property 3: There exist some positive constants m_{1em}, m_{2em}, m_{1es}, m_{2es}, c_{em}, c_{es}, g_{em}, g_{es} and the following three relationships hold.

$$\begin{aligned} & 0 < m_{1ei} \leq \| M_{ei} \| \leq m_{2ei} \; < \infty && (12)\\ & \| C_{ei} \| \leq c_{ei} \| \dot{x}_i \| && (13)\\ & \| g_{ei} \| \leq g_{ei} \; (i=m,s) && (14) \end{aligned}$$

For the human operator and the remote environment, we assume as follows [12].

Assumption 2:
The human operator can be modeled as non-passive system that applies any constant force on the master robot. The remote environment can be modeled as passive system that is any linear spring - damper system.

Under above assumption, the human operator is described as follows

$$F_{op}(t) = \bar{F}_{op} \tag{15}$$

where $\bar{F}_{op} \in \mathscr{R}^{n\times n}$ is any finite constant vector. The remote environment is assumed to be described as the following linear system.

$$F_{env}(t) = B_e\dot{x}_s(t) + K_e x_s(t) \tag{16}$$

where B_e, $K_e \in \mathscr{R}^{n\times n}$ are any positive semi-definite matrices.

The communication structure is assumed as shown in Fig.1, where the forward and backward communications are delayed by the functions of time varying delay $T_m(t)$ and $T_s(t)$ as follows.

Assumption 3: The communication time delay functions $T_m(t)$, $T_s(t)$ are continuously differentiable and satisfy as follows

$$0 \le T_i(t) \le T_i^+ < \infty \qquad i = m, s \tag{17}$$

where, $T_i^+ \in \mathscr{R}$ are constant upper bounds of the communication delay and we assume the upper bound of the round trip communication delay $T_{ms}^+ = T_m^+ + T_s^+$ can be measured in advance.

In addition, we assume the following two items for stability analysis.

Assumption 4: All signals belong to the extended $\mathscr{L}_2$ space.

Assumption 5: The velocities $\dot{x}_m = \dot{x}_s = 0$ for $t < 0$.

Note that there are no assumptions for $\dot{T}_m(t)$, $\dot{T}_s(t)$ Our approach taken here does not require any information about $\dot{T}_m(t)$ and $\dot{T}_s(t)$.

III. Control Objectives

We would like to design the control inputs τ_m and τ_s to achieve as follows

Control Objective 1. (Stability) The teleoperation system as shown in Fig. 1 is stable under the time varying communication delay, any environment and any finite constant operational inputs.

Control Objective 2. (Master-Slave Position Coordination) If $F_{op} = F_{env} = 0$, the position coordination error $x_e(t)$ goes to zero in $t \to \infty$.

$$x_e(t) = x_m - x_s \to 0 \quad as \quad t \to \infty, \tag{18}$$

and the master and slave positions are coordinated.

Control Objective 3. (Static Force Reflection) The static contact force in slave side are accurately transmitted to the human operator in the master side as follows

$$F_{op} = F_{env} \quad as \quad t \to \infty \tag{19}$$

Note that the Control Objective 3 means achievement at least level of ideal transparency[13]. This is a better transparency than the conventional method in [2], [3], [4].

IV. Control System Design

To achieve above control objectives, we propose a new couple of two controllers for the master and the slave. These are PD-type controller without time varying feedback gains.

The proposed control law with constant gains is now given as

$$\begin{cases} \tau_m = J_m^T[-D_p\dot{x}_m + K_p\{x_s(t - T_s(t)) - x_m\} + g_{em}] \\ \\ \tau_s = J_s^T[-D_p\dot{x}_s + K_p\{x_m(t - T_m(t)) - x_s\} + g_{es}] \end{cases} \tag{20}$$

where, D_p, $K_p \in \mathscr{R}^{n\times n}$ are positive and diagonal constant gain matrices.

Our proposed Control Law is simple PD type controller with P-control gain K_p and D-control gain D_p. D_p is the dissipation gain to stabilize the delayed P-control action and it is designed from the stability analysis.

Note that the Control Law requires the position and velocity signals and does not require rate of change of the delay signals. The explicit position control makes an improvement of the position coordination and force reflecting performance in comparison with the conventional scattering-based teleoperation [2], [3], [4].

The time varying gains depending on the rate of delay have been proposed in [4] to stabilize the closed-loop system for time varying delays. However, our proposed Control Law does not utilize the widely utilized scattering transformation.

V. Stability Analysis

To facilitate the stability analysis of the system, the closed loop system is now derived. The equilibrium points of the positions of the master and the slave are defined as $\bar{x}_m \in \mathscr{R}^{n\times 1}$, $\bar{x}_s \in \mathscr{R}^{n\times 1}$ such that

$$\bar{F}_{op} = K_p(\bar{x}_m - \bar{x}_s) \tag{21}$$

$$0 = K_e\bar{x}_s - K_p(\bar{x}_m - \bar{x}_s) \tag{22}$$

The new position variables with the origin of above equilibrium points are defined as follows

$$\tilde{x}_m(t) = x_m(t) - \bar{x}_m \tag{23}$$

$$\tilde{x}_s(t) = x_s(t) - \bar{x}_s \tag{24}$$

Substituting equations (15), (16), (21), (22), (23), (24) into the equation (11), then we can get the following closed-loop system.

$$\begin{cases} M_{em}\ddot{x}_m + C_{em}\dot{x}_m \\ \qquad = -D_p\dot{x}_m + K_p\{\tilde{x}_s(t - T_s(t)) - \tilde{x}_m\} \\ M_{es}\ddot{x}_s + C_{es}\dot{x}_s \\ \qquad = -D_p\dot{x}_s + K_p\{\tilde{x}_m(t - T_m(t)) - \tilde{x}_s\} \\ \qquad - B_e\dot{x}_s - K_e\tilde{x}_s \end{cases} \tag{25}$$

The following theorem is obtained concerning the closed-loop stability with the proposed Control Law.

Theorem 1: Consider the nonlinear teleoperation described by equation (25) with *Assumptions 1-5*. Then for range of the proportional control gain K_p as follows

$$K_p < \frac{2}{T_{ms}^+} D_p \tag{26}$$

the origin of the state variables $\dot{x}_m$, $\dot{x}_s$, $\tilde{x}_m$, $\tilde{x}_s$ are asymptotically stable and $\lim_{t\to\infty} x_m = \bar{x}_m$, $\lim_{t\to\infty} x_s = \bar{x}_s$.

Note that the Control Law requires the position and velocity signals and does not require rate of change of the delay signals. Hence the stability condition also does not depend on the rate of change of the delay signals and the closed-loop system is stable for any rate of change of the delay signals.

This means the Control Objective 1 is achieved.

Proof: Define a function with variables $\dot{x}_m$, $\dot{x}_s$, $\tilde{x}_m$, $\tilde{x}_s$ for the system (25) as

$$\begin{aligned} V_{ms}(x,t) &= \dot{x}_m^T(t)M_{em}\dot{x}_m(t) + \dot{x}_s^T(t)M_{es}\dot{x}_s(t) \\ &+\{\tilde{x}_m(t)-\tilde{x}_s(t)\}^T K_p\{\tilde{x}_m(t)-\tilde{x}_s(t)\} \\ &+\tilde{x}_s^T(t)K_e\tilde{x}_s(t) \end{aligned} \tag{27}$$

Property 1 gives that M_{em}, M_{es}, K_p, K_e are positive definite and the function V_{ms} is also positive definite.

The derivative of the above function V_{ms} along a trajectory of the system (25) is given by *Property 2* as

$$\begin{aligned} \dot{V}_{ms} &= \dot{x}_m^T\dot{M}_{em}\dot{x}_m + 2\dot{x}_m^T M_{em}\ddot{x}_m \\ &+\dot{x}_s^T\dot{M}_{es}\dot{x}_s + 2\dot{x}_s^T M_{es}\ddot{x}_s \\ &+2(\dot{x}_m-\dot{x}_s)^T K_p(\tilde{x}_m-\tilde{x}_s)+2\dot{x}_s^T K_e\tilde{x}_s \\ &= \dot{x}_m^T\dot{M}_{em}\dot{x}_m + \dot{x}_s^T\dot{M}_{es}\dot{x}_s \\ &+2\dot{x}_m^T\left\{-C_{em}\dot{x}_m - D_p\dot{x}_m\right. \\ &\left.+K_p\{\tilde{x}_s(t-T_s(t))-\tilde{x}_m\}\right\} \\ &+2\dot{x}_s^T\left\{-C_{es}\dot{x}_s - D_p\dot{x}_s\right. \\ &\left.+K_p\{\tilde{x}_m(t-T_m(t))-\tilde{x}_s\} - B_e\dot{x}_s - K_e\tilde{x}_s\right\} \\ &+2(\dot{x}_m-\dot{x}_s)^T K_p(\tilde{x}_m-\tilde{x}_s)+2\dot{x}_s^T K_e\tilde{x}_s \\ &= \dot{x}_m^T\{\dot{M}_{em}-2C_{em}\}\dot{x}_m \\ &+2\dot{x}_m^T\left\{-D_p\dot{x}_m + K_p\{\tilde{x}_s(t-T_s(t))-\tilde{x}_m\}\right\} \\ &+\dot{x}_s^T\{\dot{M}_{es}-2C_{es}\}\dot{x}_s \\ &+2\dot{x}_s^T\left\{-D_p\dot{x}_s + K_p\{\tilde{x}_m(t-T_m(t))-\tilde{x}_s\}\right\} \\ &+2(\dot{x}_m-\dot{x}_s)^T K_p(\tilde{x}_m-\tilde{x}_s) \\ &-2\dot{x}_s^T K_e\tilde{x}_s + 2\dot{x}_s^T K_e\tilde{x}_s - 2\dot{x}_s^T B_e\dot{x}_s \\ &= 2\dot{x}_m^T\left\{-D_p\dot{x}_m + K_p\{\tilde{x}_s(t-T_s(t))-\tilde{x}_m\}\right\} \\ &+2\dot{x}_s^T\left\{-D_p\dot{x}_s + K_p\{\tilde{x}_m(t-T_m(t))-\tilde{x}_s\}\right\} \\ &+2(\dot{x}_m-\dot{x}_s)^T K_p(\tilde{x}_m-\tilde{x}_s) - 2\dot{x}_s^T B_e\dot{x}_s \\ &= 2\dot{x}_m^T\left\{-D_p\dot{x}_m + K_p\{\tilde{x}_s(t-T_s(t))-\tilde{x}_m\}\right\} \\ &+2\dot{x}_s^T\left\{-D_p\dot{x}_s + K_p\{\tilde{x}_m(t-T_m(t))-\tilde{x}_s\}\right\} \\ &+2x_m{}^T K_p(\tilde{x}_m-\tilde{x}_s) - 2x_s{}^T K_p(\tilde{x}_m-\tilde{x}_s) - 2\dot{x}_s^T B_e\dot{x}_s \\ &= 2\dot{x}_m^T\left\{-D_p\dot{x}_m + K_p\{\tilde{x}_s(t-T_s(t))-\tilde{x}_s\}\right\} \\ &+2\dot{x}_s^T\left\{-D_p\dot{x}_s + K_p\{\tilde{x}_m(t-T_m(t))-\tilde{x}_m\}\right\} \\ &-2\dot{x}_s^T B_e\dot{x}_s \end{aligned} \tag{28}$$

Finally, we can get

$$\begin{aligned} \dot{V}_{ms} &= -2\dot{x}_m^T D_p\dot{x}_m - 2\dot{x}_s^T D_p\dot{x}_s - 2\dot{x}_s^T B_e\dot{x}_s \\ &-2\dot{x}_m^T K_p\int_0^{T_s(t)}\dot{x}_s(t-\xi)d\xi \\ &-2\dot{x}_s^T K_p\int_0^{T_m(t)}\dot{x}_m(t-\xi)d\xi \end{aligned} \tag{29}$$

Integrating the above equation in $[0,t_f]$, the following inequality can be obtained.

$$\begin{aligned} \int_0^{t_f}\dot{V}_{ms}d\tau &= -2\int_0^{t_f}\dot{x}_m^T D_p\dot{x}_m d\tau - 2\int_0^{t_f}\dot{x}_s^T D_p\dot{x}_s d\tau \\ &-2\int_0^{t_f}\dot{x}_s^T B_e\dot{x}_s d\tau \\ &-2\int_0^{t_f}\dot{x}_m^T K_p\int_0^{T_s(\tau)}\dot{x}_s(\tau-\xi)d\xi d\tau \\ &-2\int_0^{t_f}\dot{x}_s^T K_p\int_0^{T_m(\tau)}\dot{x}_m(\tau-\xi)d\xi d\tau \end{aligned} \tag{30}$$

Using Schwarz inequality, Young's inequality, *Assumption 3* and *Assumption 5*, the above equation is easily transformed into

$$\begin{aligned} &\int_0^{t_f}\dot{V}_{ms}d\tau \\ &\le -2\int_0^{t_f}\dot{x}_s^T B_e\dot{x}_s d\tau - \int_0^{t_f}\dot{x}_s^T\left\{2D_p - T_{ms}^{+}K_p\right\}\dot{x}_s d\tau \\ &\quad -\int_0^{t_f}\dot{x}_m^T\left\{2D_p - T_{ms}^{+}K_p\right\}\dot{x}_m d\tau \end{aligned} \tag{31}$$

From above equation, B_e is positive definite, hence $\int_0^{t_f}\dot{V}_{ms}d\tau \le 0$ if K_p, D_p are selected to satisfy the condition (26).

Then the state $x(t) = [\dot{x}_m \;\; \dot{x}_s \;\; \tilde{x}_m \;\; \tilde{x}_s]$ is bounded because $\int_0^{t_f}\dot{V}_{ms}d\tau < 0$ and definition of V_{ms}.

Furthermore, applying Barbalat's Lemma[15] to the closed system (25), we conclude $\dot{x}_m$, $\dot{x}_s$, $\tilde{x}_m$ and $\tilde{x}_s$ are asymptotically stable.

Consequently, the closed loop system dynamics (25) implies that

$$\tilde{x}_s(t-T_s(t)) - \tilde{x}_m = 0 \tag{32}$$

$$\tilde{x}_m(t-T_m(t)) - \tilde{x}_s = K_p^{-1}K_e\tilde{x}_s \tag{33}$$

Using the fact

$$\tilde{x}_i(t-T_i(t)) = \tilde{x}_i(t) - \int_{t-T_i}^{t}\dot{\tilde{x}}_i dt \qquad i = m,s \tag{34}$$

Then we have

$$K_p^{-1}K_e\tilde{x}_s = 0 \quad as \quad t\to\infty \tag{35}$$

K_p and K_e are positive definite, then $\lim_{t\to\infty}\tilde{x}_m = \lim_{t\to\infty}\tilde{x}_s = 0$.

The equilibrium point of the system $\dot{x}_m$, $\dot{x}_s$, $\tilde{x}_m$, $\tilde{x}_s$ is asymptotically stable and the positions of master and slave arms go to $\lim_{t\to\infty}x_m = \bar{x}_m$, $\lim_{t\to\infty}x_s = \bar{x}_s$. ■

The above result only guarantees stability of the teleoperation system and, not guaranteed the convergence of the position coordination error to zero and the force reflection. In the next result, we discuss the position coordination abilities in free space and static force reflection abilities.

Corollary 1: Consider the nonlinear teleoperation described by equation (25) with *Assumptions 1-5* and the condition (26), we have the following facts.

(1) If $F_{op} = 0$ and $F_{env} = 0$, position coordination error x_e goes to zero as

$$x_e(t) = x_m - x_s \to 0 \quad as \quad t\to\infty, \tag{36}$$

and the master and slave positions are coordinated.

Proof: If $F_{op} = 0, F_{env} = 0$, the equations (21), (16) give the following

$$F_{op} = K_p(\bar{x}_m - \bar{x}_s) = 0 \tag{37}$$

$$F_{env} = B_e\dot{x}_s(t) + K_e x_s(t) = 0 \tag{38}$$

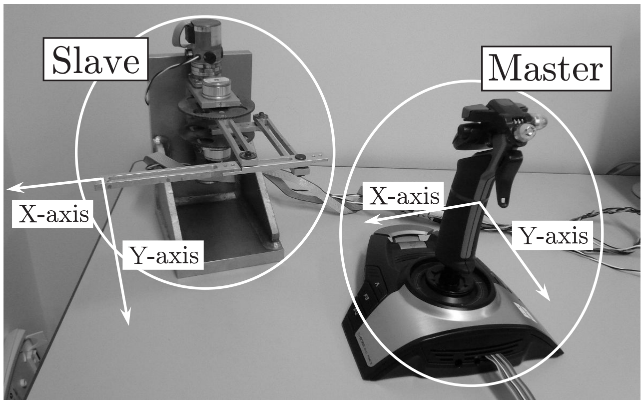

Fig. 2. Experimental Setup

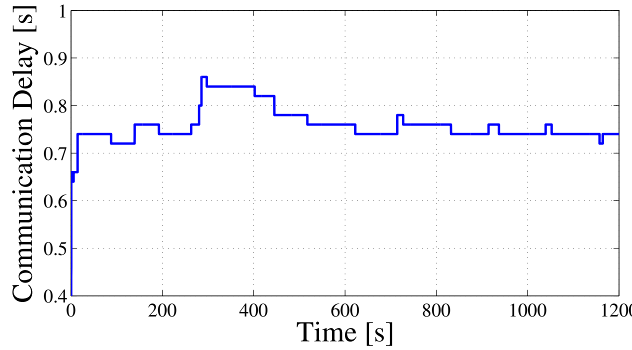

Fig. 3. Round trip delay

Theorem 1 gives $\lim_{t\to\infty}\dot{x}_s = 0$, $\lim_{t\to\infty}x_s = \bar{x}_s$, then the equation (38) should be

$$F_{env} = K_e\bar{x}_s = 0 \tag{39}$$

The above equation is substituted into (22), then

$$\bar{x}_m - \bar{x}_s = 0 \tag{40}$$

Finally the position error x_e goes to zero. ■

(2) The static force reflection in $t \to \infty$ is achieved as follows

$$F_{op} = F_{env} \tag{41}$$

Proof: *Theorem 1* implies $\lim_{t\to\infty}\dot{x}_m = 0$, $\lim_{t\to\infty}\dot{x}_s = 0$, $\lim_{t\to\infty}x_m = \bar{x}_m$, $\lim_{t\to\infty}x_s = \bar{x}_s$, then equations (16), (21), (22) lead the result

$$F_{env} = K_e\bar{x}_s = K_p(\bar{x}_m - \bar{x}_s) = F_{op} \tag{42}$$

■

Theorem 1 and *Corollary 1 (1)-(2)* correspond to *Control Objectives 1, 2, 3*, respectively. This fact proves the effectiveness of the proposed control law.

VI. Experimental Evaluation

We verify the efficacy of the proposed teleoperation methodology. The experimental setup consists of a master 2-DOF joystick, a slave parallel-link 2-DOF robot manipulator, two wireless LAN cards and two digital control systems which are connected with master or slave robots. The master and slave robots with a definition of X and Y axes are shown in Fig.2.

The two wireless LAN cards can communicate each other by using an Internet access point in the laboratory.

UDP(User Datagram Protocol) is employed as the Internet protocol and if packet loss is caused by the Internet communication, the signal can be interpolated by the previous data.

Round trip communication delay T_{ms} in our lab can be measured and one of the measured data in 1200[s] of the night time, is shown in Fig.3.

Fig.3 shows that the maxmum round trip communication delay T_{ms} is almost 0.86[s] in this period, then T^+_{ms} is selected as $T^+_{ms} = 0.9$.

The design parameters are chosen appropriately in order to achieve the condition of equation (15).

$$K_p = \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix}, \quad D_p = \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix} \tag{43}$$

Two kind of experimental conditions are given as follows.

- **Case 1** : The slave moves without any contact.
- **Case 2** : The slave moves in contact with environment.

All experimental results show that the stability is guaranteed for time varying communication delays and any human inputs as Figs. 4 and 5.

Experimental results of **Case 1** are shown in Fig.4 and results of **Case 2** are shown in Fig.5, respectively, where upper figures are for X-axes and lower figures are for Y-axes.

F_{op} and F_{env} can be estimated and calculated by control input torque. Fig. 4 shows that the slave robot manipulator accurately tracks one of the master joystick and the master-slave position coordination is achieved when the slave does not touch the environment.

Fig. 5 shows the experimental results in **Case 2**. When the slave robot is pushing the environment (2-15 [sec]), the contact torque is faithfully reflected to the operator. The operator can perceive the environment through the torque reflection. When the slave dose not contact with environment and the operator forcing is negligible (17-20[sec]), the master-slave position coordination is also achieved.

In Fig. 5, there are some errors in the force responses, but it is seems to be due to some kinds of friction caused by substantial devises of robots. These errors were not observed when a simulation without such a friction is performed.

VII. Conclusion

In this paper, we proposed a novel bilateral control strategy for nonlinear teleoperation system with time varying communication delay.

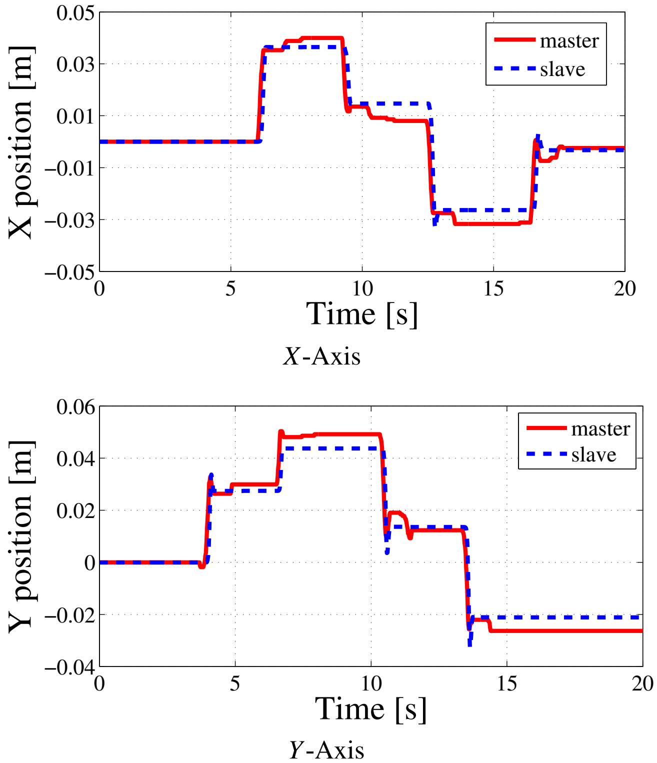

Fig. 4. Time Responses in Case 1
(without any contact to environment)

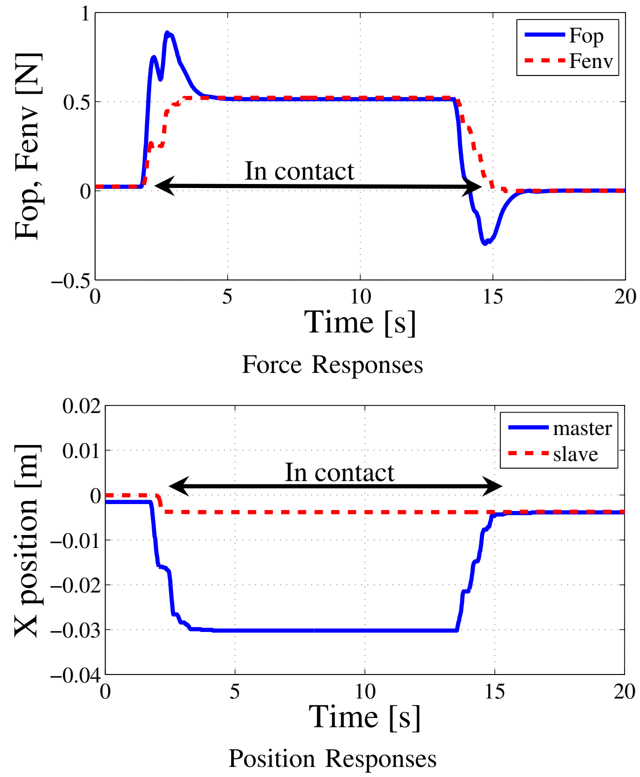

Fig. 5. Time Responses in Case 2
(Slave contacts environment)

The proposed method are simple PD-type controllers which are independent of the rate of time delay change and depend on the upper bound of round-trip delay. The proposed control strategy is independent of parameter uncertainties of the model of the robots and the operator and remote environment. The delay-dependent stability of the origin was shown via Lyapunov stability Theorem.

Furthermore the proposed strategy also achieved master-slave position coordination and bilateral static force reflection. Several experimental results with wireless communication in the Internet showed the effectiveness of the proposed strategy.

References

[1] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, Vol. 42, No. 12, pp. 2035-2057, 2006.

[2] K. Kosuge, H. Murayama and K. Takeo, "Bilateral Feedback Control of Telemanipulators via Computer Network," *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1380-1385, 1996.

[3] G. Niemeyer and J. -J. E. Slotine, "Towards Force-Reflecting Teleoperation Over the Internet," *Proc. of the IEEE International Conference on Robotics and Automation*, pp. 1909-1915, 1998.

[4] N. Chopra, M. W. Spong, S. Hirche and M. Buss, "Bilateral Teleoperation over the Internet : the Time Varying Delay Problem," *Proc. of the American Control Conference*, pp. 155-160, 2003.

[5] E. Slawinski, J. F. Postigo and V. Mut, "Bilateral teleoperation through the Internet," *Robotics and Autonomous Systems*, Vol. 55, No. 3, pp.205-215, 2007.

[6] Y.-J. Pan, , C. Canudas-de-Wit and O. Sename, "A New predictive Approach for Bilateral Teleoperation with Applications to Drive-by-Wire Systems," *IEEE Transactions on Robotics*, Vol. 22, No.6, pp.1146-1162, 2006.

[7] R. J. Anderson and M. W. Spong, "Bilateral Control of Teleoperators with Time Delay," *IEEE Transactions on Automatic Control*, Vol. 34, No. 5, pp. 494-501, 1989.

[8] G. Niemeyer and J. -J. E. Slotine, "Stable Adaptive Teleoperation," *IEEE J. of Oceanic Engineering*, Vol. 16, No. 1, pp. 152-162, 1991.

[9] N. Chopra, M. W. Spong, R. Ortega, and N. E. Barabanov, "On tracking performance in bilateral teleoperation," *IEEE Trans. on Robotics*, Vol. 22, No.4, pp. 861-866, 2006.

[10] T. Namerikawa and H. Kawada, "Symmetric Impedance Matched Teleoperation with Position Tracking," *Proc. of IEEE Conference on Decision & Control*, pp. 4496 - 4501, 2006.

[11] D. Lee and M. W. Spong, "Passive Bilateral Teleoperation With Constant Time Delay," *IEEE Trans. on Robotics,*, Vol. 22, No. 2, pp.269-281, 2006.

[12] R. Lozano, N. Chopra and M. W. Spong, "Convergence Analysis of Bilateral Teleoperation with Constant Human Input," *Proc. of the American Control Conference*, pp. 1443-1448, 2007.

[13] Y. Yokokohji and T. Yoshikawa, "Bilateral Control of Master-Slave Manipulators for Ideal Kinetic Coupling - Formulation and Experiment," *IEEE Transactions on Robotics and Automation*, Vol. 10, No.5, 1994.

[14] M. W. Spong, S. Hutchinson and M. Vidyasagar, *Robot Modeling and Control, Hoboken*, NJ: Wiley, 2006.

[15] H. K. Khalil, *Nonlinear System*, Prentice-Hall, 1996.

[16] H. Kawada and T. Namerikawa, "Bilateral Control of Nonlinear Teleoperation with Time Varying Communication Delays," *Proc. the American Control Conference*, pp. 189-194, 2008.