Delay Compensation for Nonlinear Teleoperators Using Predictor Observers

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***Abstract*—This paper presents a delay compensation technique for nonlinear teleoperators by developing a predictor type sliding mode observer (SMO) that estimates future states of the slave operator. Predicted states are then used in control formulation. In the proposed scheme, disturbance observers (DOB) are also utilized to linearize nonlinear dynamics of the master and slave operators. It is shown that utilization of disturbance observers and predictor observer allow simple PD controllers to be used to provide stable position tracking for bilateral teleoperation. Proposed approach is verified with simulations where it is compared with two state-of-the-art methods. Successful experimental results with a bilateral teleoperation system consisting of a pair of pantograph robots also validates the proposed method.**

I. Introduction

Bilateral teleoperation implies a system in which a slave robot located at a certain distance is manipulated remotely by a master system. Signals are transmitted through a communication channel from master to slave and from slave to master sides. Due to possible communication delays in the channel, the performance of the system is degraded over time and eventually becomes unstable. Stability and performance issues have been a real challenge in the field of teleoperation and numerous researchers have contributed to this field over the last decades.

Anderson and Spong [1] proved that time delays lead to non-passive communication channel. They proposed *scattering transformation* to render the communication channel passive. Their technique was able to cope with any constant delay. Along the same lines, Niemeyer and Slotine [2] later introduced a more elegant formulation in terms of wave variables.

The delay variation is unavoidable when the communication channels are influenced by other signals as in internet or satellite based transmission. Therefore, the methods proposed for constant delay have been found to be inadequate to solve time variable delay. In 1998, the wave variables method was extended to the systems with time variable delays [3]. In [4] destabilization of the system by time variable delay was shown and the method [1] developed for constant delays was extended to the variable delays. Passivity of the system was preserved by adding a time varying gain into the communication channel. The method was then adapted by introducing a feedforward control for improving the position tracking performance under time varying communication delay [5]. Performance degradation due to the time variable delay is minimized with a wave variable based method [6]. In this method the energy generated in the system is limited by introducing an energy balance monitoring technique. Communication Management Modules technique is also proposed for handling time variable delay in the framework of passivity theory [7].

In 1998, Sano designed controllers for different values of bounded delay and used gain scheduling [8]. In 1995, H_∞ control and μ analysis and synthesis technique [9] were developed where stability and performance against time delay were considered together.

Recently new techniques have been proposed for preserving stability of bilateral teleoperation which do not employ scattering transformation. In [10] degradation of the tracking performance is addressed and a method that introduces position control on both the master and slave robots is proposed. Stability of the bilateral system has been proved using a Lyapunov type analysis. Simple P-like and PD-like position controllers which provide global position tracking for nonlinear teleoperators are proposed in [11].

Observer based approaches are also developed for time delay compensation in bilateral control systems. The method proposed in [12] treats the delay as a network disturbance created by the communication medium and designs the so-called "Communication Disturbance Observer (CDOB)" at the master side to estimate and compensate this network disturbance.

In this work, a predictor observer is proposed for position control of nonlinear teleoperators. Disturbance observers and a predictor type sliding mode observer are employed for the purpose of linearization of both teleoperators and prediction of slave's future states (position and/or velocity). Once the

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nonlinear dynamics of the slave teleoperator is linearized by disturbance observer (DOB), sliding mode observer (SMO) is able to predict the future states of the slave since nominal slave model is used in SMO. Future states of the slave are used as feedback signal for the closed loop control system at the master side, hence the destabilizing effect of the time delay is avoided and the stability of the teleoperation system is attained. Several simulations and experimental results are presented to demonstrate performance of the proposed ideas. Comparison with some existing techniques are also provided in simulations.

The paper is organized as follows. Section II briefly describes bilateral teleoperation systems. Section III describes the linearization of the nonlinear slave dynamics using disturbance observer. Section IV is on the design of the sliding mode observer and compensation of the time delay. In Section V, the proposed method is compared with two well-known methods in simulations using 2-DOF robots. Section VI presents experimental results obtained with a pair of pantograph robots working in master-slave configuration. Section VII concludes the paper with some remarks and indicates possible future directions.

II. Bilateral Teleoperation

A bilateral teleoperation system is usually composed of a human operator, a master system, communication channel, a slave system and environment (Fig. 1). In the literature different bilateral control architectures are proposed based on the type of shared signals (position, velocity and force). In some of these architectures, control systems are based on observers that estimate certain state variables. In these observer based approaches, the control input (force or torque) for the slave is computed at the master side and sent to the slave side whereas position (and/or velocity) of the slave is fed back to the master side and used in control calculations.

Fig. 1. Bilateral Teleoperation System

In order to analyze bilateral systems, a n-DOF bilateral control system is employed in discussions. In such a system, slave is a n DOF robot arm and its dynamics is modeled as

$$\tau_s = D_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + F_{Gs}(q_s) + B_s\dot{q}_s + \tau_{ds} \quad (1)$$

where q_s is the vector of joint angles, $D_s(q_s)$ is the $n \times n$ positive-definite inertia matrix, $C_s(q_s, \dot{q}_s)$ is the $n \times n$ coriolis-centripetal matrix, $F_{Gs}(q_s)$ is the $n \times 1$ gravitational force vector, B_s is the viscous friction (damping) matrix and τ_{ds} is an external disturbance vector. Input torque vector which is the difference between the manipulator torque and the environmental torque is represented by τ_s. Likewise, master robot which is manipulated by a human operator can be described similarly as

$$\tau_m = D_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + F_{Gm}(q_m) + B_m\dot{q}_m + \tau_{dm} \quad (2)$$

where subscript m emphasizes the fact that related quantities belong to the master robot. τ_m is net input torque vector defined as the difference between the torque applied by the operator and the torque generated by the manipulator. Note that this bilateral system can be stabilized by a PD controller if there is no delay in the communication channel. On the other hand, even a very small amount of delay (e.g. $0.05 - 0.1$ sec) can degrade the performance and finally makes the system unstable.

III. Linearization of Nonlinear Teleoperators

A disturbance observer (DOB) [14] is designed in this section. It linearizes the system dynamics and eliminates external disturbances and parametric uncertainties. Utilization of disturbance observer implies a linear system with nominal parameters which in turn allows application of the predictor observer.

The nonlinear teleoperator dynamics given in (1) and (2) can be written without subindices as

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + F_G(q) + B\dot{q} + \tau_d = \tau \quad (3)$$

where the inertia matrix $D(q)$, coriolis-centripetal matrix $C(q, \dot{q})$, gravitational force vector $F_G(q)$, viscous friction (damping) matrix B and an external disturbance vector τ_d are the source of nonlinearities, uncertainties and external disturbances.

We first note that inertia and damping matrices can be written as

$$D(q) = D_{nom} + \tilde{D}(q)$$

and

$$B = B_{nom} + \tilde{B}$$

where the nominal inertia and damping matrices are defined as

$$D_{nom} = diag(J_{nom_1}, J_{nom_2}, \ldots, J_{nom_n})$$

and

$$B_{nom} = diag(b_{nom_1}, b_{nom_2}, \ldots, b_{nom_n})$$

Rewriting (3) in terms of nominal inertia and damping matrices imply

$$D_{nom}\ddot{q} + B_{nom}\dot{q} + \tau_{dis} = \tau \quad (4)$$

where τ is the control input and τ_{dis} is the total disturbance acting on the system which is defined as

$$\tau_{dis} = \tilde{D}(q)\ddot{q} + C(q, \dot{q})\dot{q} + \tilde{B}\dot{q} + F_G(q) + \tau_d \quad (5)$$

where $\tilde{(.)}$ represents the difference between the actual and nominal quantities. In order to estimate the total disturbance at each joint, a disturbance observer is integrated to each joint of the teleoperator.

For an n-DOF teleoperator, (4) implies n first order differential equations of the form

$$J_{nom_i}\ddot{q}_i + b_{nom_i}\dot{q}_i + \tau_{dis_i} = \tau_i, \quad i = 1, \ldots, n \tag{6}$$

For simplicity we analyze the system through a single ith joint. Substituting $\omega_i = \dot{q}_i$ into equation (6) and taking Laplace transform, we obtain

$$\tau_{dis_i}(s) = -J_{nom_i} s w_i(s) - b_{nom_i} w_i(s) + \tau_i(s) \tag{7}$$

$\tau_{dis_i}(s)$ can be estimated by a low-pass filter. To this end, both sides of the above equation is multiplied by the transfer function of a low-pass filter, $G(s) = \frac{g}{s+g}$, namely

$$G(s)\tau_{dis_i}(s) = G(s)(-J_{nom_i} s w_i(s) - b_{nom_i} w_i(s) + \tau_i(s)) \tag{8}$$

where g is the cut-off frequency of the filter. Rearranging the equation, we obtain

$$G(s)\tau_{dis_i}(s) = -\frac{s}{s+g} g J_{nom_i} w_i(s) - G(s)(b_{nom_i} w_i(s) - \tau_i(s)) \tag{9}$$

Defining the estimated disturbance as $\hat{\tau}_{dis_i}(s) = G(s)\tau_{dis_i}(s)$, and replacing the term $\frac{s}{s+g}$ by $1 - \frac{g}{s+g}$, it follows that

$$\hat{\tau}_{dis_i}(s) = G(s)(-b_{nom_i} w_i(s) + \tau_i(s)) - (1 - G(s)) g J_{nom_i} w_i(s) \tag{10}$$

Lemma 1. *The total disturbance on the system is eliminated in the low frequency range by adding the estimated disturbance given in (10) to the system as an input torque $\tau_i(s) \leftarrow \tau_i(s) + \hat{\tau}_{dis_i}(s)$.*

Proof: Substituting $\tau_i(s) \leftarrow \tau_i(s) + \hat{\tau}_{dis_i}(s)$ into (7) and recalling that the estimated disturbance is given by $\hat{\tau}_{dis_i}(s) = G(s)\tau_{dis_i}(s)$ yields

$$J_{nom_i} s w_i(s) + b_{nom_i} w_i(s) = \tau_i(s) - (1 - G(s))\tau_{dis_i}(s) \tag{11}$$

Note that the total disturbance torque on the ith joint is completely eliminated if $G(s) \approx 1$. Therefore the dynamics of the ith joint of a robot manipulator in the low-frequency range implies a nominal plant of the form

$$J_{nom_i} s w_i(s) + b_{nom_i} w_i(s) = \tau_i(s) \tag{12}$$

■

IV. Observer Based Time Delay Compensation in Bilateral Teleoperation

In observer based approaches presented in the literature, control input of the slave is computed at master side and transmitted to the slave side through the communication channel. Position or velocity of slave is fed back to the master side through the same channel (Fig. 2).

Linearized slave dynamics, as explained in section III, can be written as the following scalar differential equations in state-space for each joint:

$$\dot{p}(t) = \omega(t) \tag{13}$$

$$J_s\dot{\omega}(t) + b_s\omega(t) = \tau_s(t) \tag{14}$$

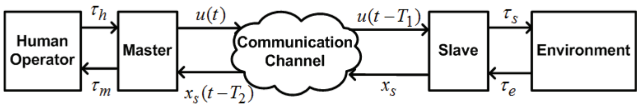

Fig. 2. Sharing control input and position signals in observer based teleoperation systems

Suppose the time delays from master to slave and from slave to master are denoted by T_1 and T_2, respectively, and they are constant. The input to the slave robot will be $\tau_s = u(t - T_1)$ assuming no interaction between the slave and the environment. On the other hand, the position of the slave will reach to the master side as $p_d(t) = p(t - T_2)$(see Fig. 2).

In order to predict position (and/or velocity) of the slave system, we construct the following sliding mode observer (SMO):

$$\dot{\hat{p}}(t) = \hat{\omega} \tag{15}$$

$$J_s\dot{\hat{\omega}}(t) + b_s\omega_e(t) = u(t) + u_o(t) \tag{16}$$

$$J_s\dot{\omega}_e(t) = J_s\dot{\omega}_d(t) - u_{oeq}(t) \tag{17}$$

$$\dot{p}_e(t) = \omega_e \tag{18}$$

where $\hat{p}$ and $\hat{\omega}$ are observer's intermediate variables and p_e and ω_e are estimated angular position and velocity of the slave. SMO input and its equivalent part are denoted as u_o and u_{oeq}. In order to design the observer input, an observer error is defined as the difference between the delayed position $p_d(t)$ and the intermediate variable $\hat{p}(t)$, as

$$e(t) = p_d(t) - \hat{p}(t) \tag{19}$$

Since the observer input will be designed in SMC (sliding mode control) framework, a sliding surface is defined in terms of observer error as

$$\sigma = \dot{e}(t) + Ce(t) \tag{20}$$

where $C > 0$ is the slope of the sliding surface. In sliding mode control (SMC) theory, the control that keeps the system on the sliding surface is called *equivalent control*. Since $\sigma = 0$ when the system is on the sliding surface, equivalent control can be computed by setting $\dot{\sigma}$ to zero. Since $\dot{\sigma}$ necessitates the first and the second derivatives of the observer error, we calculate them explicitly as

$$\dot{e}(t) = \dot{p}_d(t) - \dot{\hat{p}}(t) = \omega_d(t) - \hat{\omega}(t) \tag{21}$$

and

$$\ddot{e}(t) = \dot{\omega}_d(t) - \dot{\hat{\omega}}(t) = \dot{\omega}_d(t) + \frac{1}{J_s}(b_s\omega_e(t) - u(t) - u_o(t)) \tag{22}$$

In light of (21) and (22), we have

$$\dot{\sigma} = \dot{\omega}_d(t) + \frac{b_s}{J_s}\omega_e(t) - \frac{1}{J_s}u(t) - \frac{1}{J_s}u_o(t) + C\dot{e}(t) \tag{23}$$

By setting $\dot{\sigma}$ to zero, we get the so-called equivalent control

$$u_{oeq}(t) = J_s\dot{\omega}_d(t) + b_s\omega_e(t) - u(t) + J_sC\dot{e}(t) \tag{24}$$

Observer input can be defined as the sum of the equivalent control $u_{oeq}(t)$ and a discontinuous term ($Ksgn(\sigma)$); i.e.

$$u_o(t) = u_{oeq}(t) - Ksgn(\sigma) \tag{25}$$

where $K > 0$ is a gain parameter and $sgn(.)$ denotes the well-known signum function. It is straightforward through a Lyapunov analysis to show that the control law given in (25) can bring the system onto the sliding surface from arbitrary initial conditions in state-space and asymptotically stabilizes there.

Lemma 2. *The observer defined by the equations in (15)-(18) predicts the future position (and/or velocity) of the slave system.*

Proof: Substituting the equivalent control given by (24) into (17) implies

$$J_s\dot{\omega}_e(t) = -b_s\omega_e(t) + u(t) - J_sC\dot{e}(t) \tag{26}$$

Since (13) and (14) are defined for all t, one can replace t by $t - T_2$ and rewrite equations as

$$\dot{p}(t - T_2) = \omega(t - T_2) \tag{27}$$

$$J_s\dot{\omega}(t - T_2) + b_s\omega(t - T_2) = \tau_s(t - T_2) \tag{28}$$

Since $p_d = p(t-T_2)$, $\omega_d(t) = \omega(t-T_2)$ and $\tau_s(t-T_2-T_1) = u(t-(T_1+T_2))$, the following differential equation is obtained in terms of delayed signals:

$$\dot{p}_d(t) = \omega_d(t) \tag{29}$$

$$J_s\dot{\omega}_d(t) + b_s\omega_d(t) = u(t - T) \tag{30}$$

where $T = T_1 + T_2$ is the total round-trip delay.

Replacing t by $t + T$ in (30) implies

$$J_s\dot{\omega}_d(t + T) + b_s\omega_d(t + T) = u(t + T - T) = u(t) \tag{31}$$

By subtracting (31) from (26) we obtain

$$J_s(\dot{\omega}_e(t) - \dot{\omega}_d(t + T)) + b_s(\omega_e(t) - \omega_d(t + T)) = -J_sC\dot{e}(t) \tag{32}$$

Defining $\tilde{\omega}(t) = \omega_e(t) - \omega_d(t+T)$ and rewriting (32) implies

$$J_s\dot{\tilde{\omega}} + b_s\tilde{\omega} = -J_sC\dot{e}(t) \tag{33}$$

At steady-state, derivatives that appear in above equation converge to zero. Therefore, solution of (33) as $t \to \infty$ becomes

$$\lim_{t\to\infty} \tilde{\omega}(t) = 0 \tag{34}$$

Since $\tilde{\omega}(t) = \omega_e(t) - \omega_d(t + T)$, it follows that

$$\lim_{t\to\infty} \omega_e(t) = \omega_d(t + T) \tag{35}$$

Recall that $\omega_d(t) = \omega(t - T_2)$, and thus $\omega_d(t + T) = \omega(t + T - T_2) = \omega(t + T_1)$. Hence the final result is

$$\lim_{t\to\infty} \omega_e(t) = \omega_d(t + T) = \omega(t + T_1) \tag{36}$$

This shows that the sliding mode observer (SMO) predicts future values of slave's velocity. ■

Estimated (or predicted) velocity $\omega_e(t) = \omega(t+T_1)$ and its integral $p_e = p(t + T_1)$ can be used in controller design (see Figure 3).

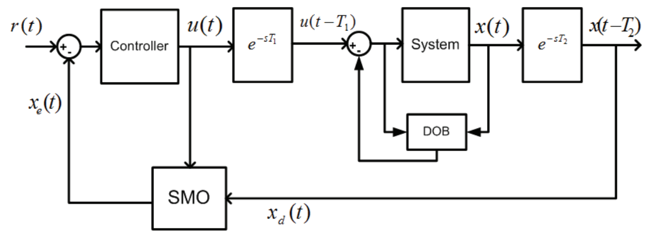

Fig. 3. SMO Based Bilateral Control System.

Control signal $u(t)$ for the slave can be designed as

$$u(t) = f(X_e(t)) = f(p_e(t), \omega_e(t)) \tag{37}$$

where $f(.)$ is a linear or nonlinear function. For instance, $f(.)$ could represent a linear control such as PD or a robust nonlinear control such as SMC (sliding mode control). Since the designed control input is delayed by T_1 through the channel, in light of (37) slave control input $\tau_s(t)$ can be written as

$$\begin{aligned}\tau_s &= u(t - T_1) = f(p_e(t - T_1), \omega_e(t - T_1)) \\ &= f(p_d(t + T_2), \omega_d(t + T_2)) = f(p(t), \omega(t))\end{aligned} \tag{38}$$

Equation (38) shows that the slave control input $\tau_s(t)$ is designed in terms of non-delayed signals, and thus the slave system is automatically stable.

V. Simulations

In order to show the effectiveness of the proposed method, simulation results are presented in this section. The simulations of P-like controller and CDOB are also demonstrated for comparison purpose. The master and slave manipulators are modeled as a pair of 2-DOF scara robots.

Simulations have been carried out in Matlab/Simulink where a time variable delay characterized by a random variable with a mean of 0.5 sec. exists in the communication channel. The master and the slave teleoperators move freely in space, and both have same initial positions. The proposed method is compared with two methods that have different architectures, namely *P-like controller* technique [11] based on damping injected proportional gain controllers and *Communication Disturbance Observer (CDOB)* method [12] based on an observer.

The simulation results, in cartesian space, are depicted in Fig. 4 for the teleoperators using the proposed method. In this figure, it is clear that the slave teleoperator (dashed line) successfully tracks the master teleoperator trajectory (solid line) with average 0.5 sec delay and both teleoperators converge same position when master teleoperator stands still.

Simulation results are depicted in Fig. 5 for the P-like controller and in Fig. 6 for CDOB approach, respectively. In implementation of P-like controller viscous friction B is assumed to be known and compensated by adding $B\dot{q}$ to the input, however in CDOB approach viscous friction is rejected

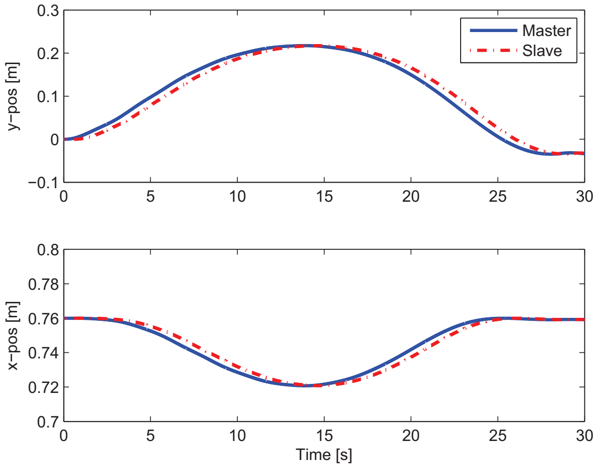

Fig. 4. Position tracking performance for Observer Based Approach

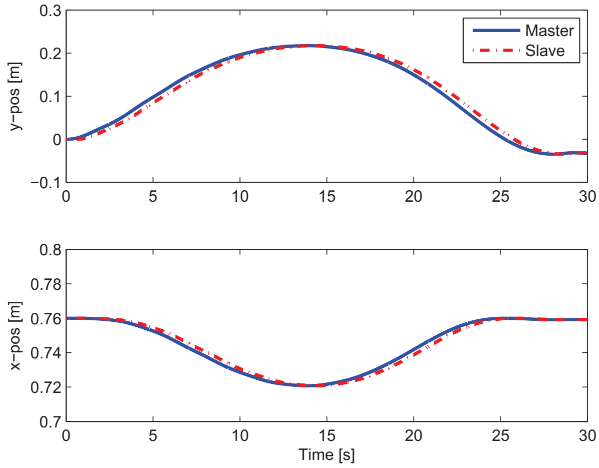

Fig. 6. Position tracking performance for CDOB

by the observer as in our method. The simulation results of two methods are comparable with our observer based approach in terms of position tracking performance and all three of them are able track the same master trajectories.

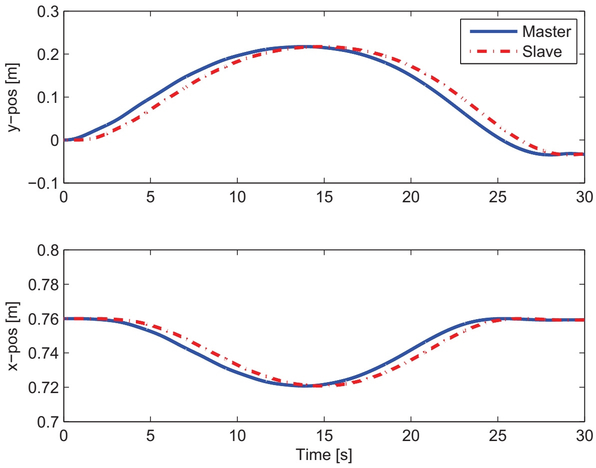

Fig. 5. Position tracking performance for P-like Controller

VI. Experimental Results

Two pantograph robots (Fig. 7) designed and manufactured in our labs are used in a bilateral control system as master and slave systems. Linearization of nonlinear dynamic of pantograph robots are attained by disturbance observer given in section III and SMO based time delay compensation method is employed on these pantograph robots to demonstrate the effectiveness of our proposed approach.

In the experiment, the end-effector positions of the pantographs in $x - y$ plane and joint angles are examined. The aim is to enable the slave robot to follow master's trajectories generated by human operator. Pantographs are allowed to work

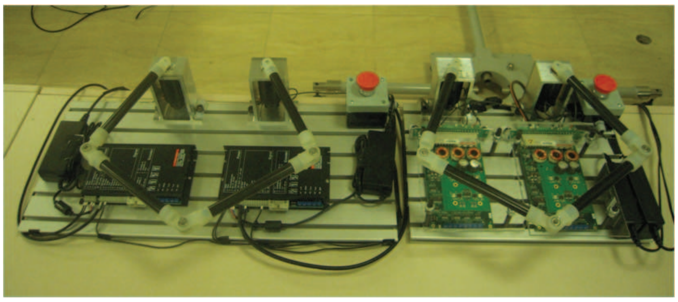

Fig. 7. Master and slave pantograph robots

in a bilateral teleoperation system by introducing a variable time delay characterized by a normally distributed random variable with a mean of 0.5 sec and standard deviation of 0.025 sec. Time delay is artificially created with Matlab's Time-Variable Delay block. Control algorithms are implemented in real-time using dSpace1103 controller board. The cut-off frequency of the low-pass filter, $G(s)$, used in the disturbance observer is set to $g = 1000$ rad/sec.

Number 5 shaped reference (an open curve) is drawn by the operator controlled master pantograph. As shown in Fig. 8, the end-effector of slave pantograph (dashed line) successfully tracks the end-effector of master pantograph (solid line). Angular joint positions of pantographs are depicted in Fig. 9. Note that joint angles of pantographs track each other with a delay. This is inevitable since the future values of operator reference can not be known in advance.

Experimental results presented above indicate that the nonlinear dynamics of pantograph robots are successfully linearized and the parameter uncertainties in the system are eliminated by the disturbance observer (DOB) which in turn allows implementation of SMO for delay compensation. In all experiments slave pantograph successfully tracks the trajectory of the master pantograph.

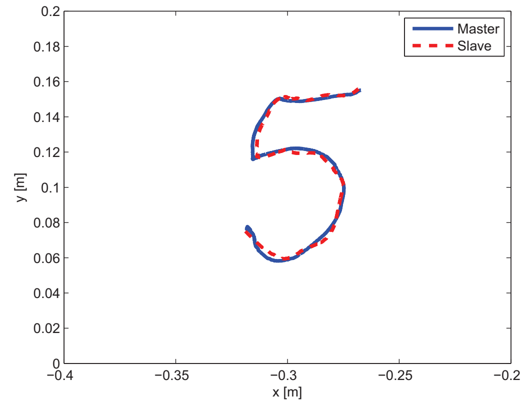

Fig. 8. Tracking the reference (number 5) drawn by the master

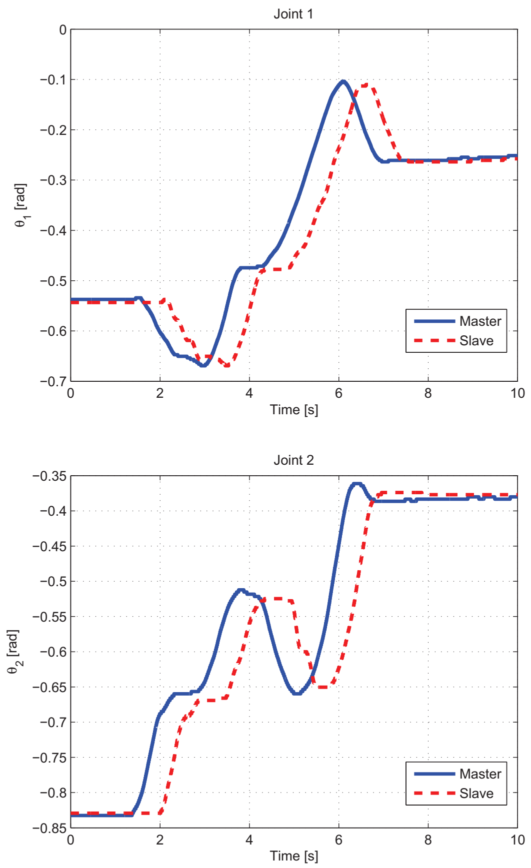

Fig. 9. Joint positions versus time

VII. Conclusion and Future Works

In this paper, a predictor observer based delay compensation method is proposed to provide robust position tracking performance of a nonlinear bilateral teleoperation system. A disturbance observer is employed on both master and slave teleoperators to linearize their nonlinear dynamics by rejecting total disturbance. Future position and/or velocity of slave teleoperator is predicted by the proposed sliding mode observer. By using predicted states as feedback signals, simple PD controllers establish stable position tracking with satisfactory performance for a nonlinear bilateral teleoperation system. Simulations, which have been carried out for a bilateral teleoperation system consisting of a pair of scara robots, demonstrated that position tracking performance of proposed method is comparable with two different methods, P-like controller and CDOB. Proposed delay compensation technique is also verified with successful experimental results with a bilateral teleoperation system consisting a pair of pantograf robots.

As a future work, we plan to work on force reflecting teleoperator systems in the same observer framework.

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