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Improved Transparency in Bilateral Teleoperation with Variable Time Delay

Ali Shahdi and Shahin Sirouspour

Department of Electrical and Computer Engineering, McMaster University, Canada
shahdisa@mcmaster.ca, sirouspour@ece.mcmaster.ca

***Abstract*— Communication time delay has been a major barrier to achieving high performance while maintaining stability in bilateral teleoperation. Building upon the results of our recent work in [1], a provably stable adaptive controller is proposed for *variable delay* teleoperation. The controller utilizes a model of the system dynamics and the time delay within a predictive control framework to improve the response transparency. It can also adapt to uncertainties in the user and environment dynamics. The performance objectives are delay-free position tracking between the master and slave and the establishment of a virtual mass-damper tool impedance between the user and environment. Delay reduction is accomplished based on a state observer and estimates of the system parameters. Using the delay reduced dynamics, an adaptive output regulation problem is formulated and solved. A Lypunov-based analysis of the performance and stability of the resulting system is presented. Simulation results with a single-axis teleoperation setup demonstrate the effectiveness of the proposed approach.**

***Index Terms*— Teleoperation, Variable time delay, Transparency, Adaptive control, Haptics, Model-predictive control.**

I. Introduction

It is well recognized in the literature that the communication time delay between the master and slave sites can severely degrade the transparency and stability of bilateral teleoperation [2], [3]. In [3], the robust stability of a number of bilateral teleoperation architectures with respect to time delay is analyzed. Some of the existing time-delay teleoperation controllers have been compared from stability and performance perspectives in [4]. A large number of existing time-delay teleoperation controllers employ the scattering theory and the concept of passivity to attain guaranteed stability, e.g. see [5], [6], [7] among other references. In passivity-based methods, however, enhanced robust stability is often gained at the expense of a highly reduced transparency. Consequently, several variations of the wave transformation-based control approach have been developed to improve its transparency [8], [9].

A main drawback of many time-delay teleoperation controllers, particularly a great number of passivity-based techniques, is their lack of a mechanism for incorporating available model information into the control design. This has led the authors of this paper to investigate the use of model-based control techniques for time-delay teleoperation [10], [11], [12], [13], [1]. In [10], a discrete-time state-space formulation of teleoperation was presented in which the communication delay is augmented into the system states resulting in a delay-free output feedback control problem. To improve computational efficiency, a continuous-time formulation of the controller was later introduced in [11]. More recently a decentralized version of the model-based LQG controller was shown to improve the robust stability of the system [12].

The use of model and delay information in the above model-based control methods improves the transparency but the controllers can be sensitive to modeling uncertainties, particularly those in the environment and operator dynamics. This problem was partly mitigated by using a multi-model switching control strategy. However, it is difficult to prove the stability of such switching controller. In [13], the issue of robust stability was addressed by proposing an H_∞-based model predictive teleoperation controller.

The robust controller in [13] is less sensitive to modeling uncertainties compared to our earlier model-based controllers. Nonetheless, given that a fixed controller is used for the entire range of operation, the transparency may still be sacrificed particulary if large modeling uncertainty is considered. Our recent work in [1] addresses this issue by introducing an *adaptive* model predictive controller for time-delay teleoperation. This new controller builds on our earlier model-based controller in [11] to adapt to modeling uncertainty. It generalizes some of the concepts introduced in [14] for the control of a first-order single-input/single-output time-delay system to a multi-input/multi-output teleoperation control.

In this paper, the controller in [1] is modified to accommodate for a known but *variable* time delay. Delay reduction is achieved through a suitable predictive state transformation using estimated model parameters. Teleoperation transparency is attained by regulating properly defined output signals for the delay-reduced dynamics. A Lyapunov analysis is employed to demonstrate closed-loop stability and to derive the parameter adaptation laws.

The rest of this paper is organized as follows. The dynamics of the master and slave devices are discussed in Section II. A state-space formulation of the teleoperation dynamics is presented in Section III. In Section IV, the proposed model reduction and state prediction techniques are introduced. In Section V, an output regulation control for achieving the teleoperation objectives is discussed. The proof of stability and the derivation of the adaptation law are also given in this section. A design example along with the results of numerical simulations are presented in Section VI. Finally, the paper is

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concluded in Section VII.

II. Dynamics of Master/Slave Teleoperation Systems

In this work, a centralized teleoperation control architecture is assumed in which the teleoperation controller resides at master side, as shown in Fig. 1. The controller receives the force and position/velcoity signals and sends the control actions from and to the both sides subject to communication delay. There is $\tau_1(t)$ delay for the slave control signal to arrive at the slave and $\tau_2(t)$ delay for slave measurements to reach the controller. Note that in general the communication delays can be a function of time.

The haptic interfaces employed in teleoperation are generally rigid multi-body mechanical devices with the second-order nonlinear dynamics. As shown in our paper in [11], an adaptive feedback linearizing control scheme can be employed to transform these nonlinear dynamics into linear dynamics. The dynamics of the slave robot are also generally second-order and nonlinear and can be similarly linearized through the application of local dynamic adaptive feedback linearizing control laws.

The linearized master/slave dynamics become decoupled in different axes of motion if the user and environment dynamics are assumed decoupled. Such assumption leads to the decoupling of the control design into single-axis problems yielding considerable simplification in the control synthesize. Therefore, throughout the rest of the paper only a single-axis problem will be considered although the proposed solution can be generalized to the case in which the linearized dynamics are coupled among the axes of motion.

The linearized single-axis dynamics of master robot can be written as

$$m_m\ddot{x}_m + b_m\dot{x}_m + k_m x_m = f_{cm} + f_h \tag{1}$$

where m_m, b_m, and k_m are mass, damping, and stiffness of the master interface, and x_m is its position; f_{cm} is the control signal and f_h is the operator/device interaction force. Although the arm dynamics are generally nonlinear and time-varying, the following linear approximation of these dynamics has proven adequate in practice for teleoperation control, e.g. see [15].

$$m_h\ddot{x}_m + b_h\dot{x}_m + k_h x_m = f_h^* - f_h \tag{2}$$

In (2) m_h, b_h, and k_h are respectively, mass, damping and stiffness of the operator's arm, x_m has been defined in (1), and f_h^* is a bounded exogenous input force. This model separates the operator force into a passive mass-spring-damper type reactive component and a bounded intentional command force. The arm dynamics in (2) can be combined with the master dynamics in (1) resulting in

$$(m_m + m_h)\ddot{x}_m + (b_m + b_h)\dot{x}_m + (k_m + k_h)x_m = f_{cm} + f_h^* \tag{3}$$

Similarly, the linearized dynamics of the slave robot in one axis can be written as

$$m_s\ddot{x}_s + b_s\dot{x}_s + k_s x_s = f_{cs} - f_e \tag{4}$$

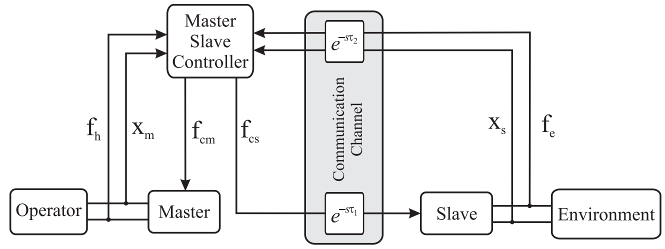

Fig. 1. Teleoperation system schematic.

where x_s is the position of the slave; m_s, b_s, and k_s are the slave mass, damping, and stiffness, respectively; f_{cs} is the control signal and f_e is the environment reaction force. The reaction force for compliant environments can be modeled by

$$f_e = m_e\ddot{x}_s + b_e\dot{x}_s + k_e x_s \tag{5}$$

This environment model can be combined with the slave dynamics in (4) to obtain

$$(m_s + m_e)\ddot{x}_s + (b_s + b_e)\dot{x}_s + (k_s + k_e)x_s = f_{cs} \tag{6}$$

III. Time-Delay Teleoperation System

Ideal transparency in teleoperation, also known as ideal kinesthetic coupling [16], can be described in terms of scaled position and force tracking between the master and slave robots [16], [17]. In practice, however, modeling and sensing errors as well as computation and control delay can easily cause instability in an ideally transparent teleoperation system [16]. To alleviate these robustness issues with the ideal transparency, a virtual intervening tool can be introduced between the operator and the environment as follows [16], [17]

$$f_h(t) = m_t\ddot{x}_t(t) + b_t\dot{x}_t(t) + k_t x_t(t) + \alpha_f f_e(t) \tag{7}$$

$$x_m(t) = \alpha_p x_s(t) \tag{8}$$

$$x_m(t) = x_t(t) \tag{9}$$

where m_t, b_t, and k_t are mass, damping, and stiffness of the virtual tool and x_t is its position. It is worth noticing that the transparency objectives used in this paper are based on delay-free tracking measures. Utilizing a model-based prediction mechanism, the proposed controller attempts to achieve these delay-free tracking goals as closely as possible.

The combined operator/master and slave/environment dynamics can be written in a state-space form suitable for the application of the proposed output-feedback teleoperation controllers. Using (3), the operator/master dynamics can be written as

$$\dot{X}_m(t) = A_m X_m(t) + B_m f_{cm}(t) + B_{f_h^*} f_h^*(t) \tag{10}$$

where $X_m(t) = \begin{bmatrix} x_m(t) & v_m(t) \end{bmatrix}^T$ is the state vector. The control signal $f_{cm}(t)$ has been introduced in (1). Similarly using (6), the state-space equations for the slave/environment subsystem can be written as

$$\dot{X}_s(t) = A_s X_s(t) + B_s f_{cs}(t) \tag{11}$$

where $X_s(t) = \begin{bmatrix} x_s(t) & v_s(t) \end{bmatrix}^T$ is the state vector and $f_{cs}(t)$ is the control signal. The desired tool dynamics in (7) can also be written as

$$\dot{X}_t(t) = A_t X_t(t) + B_t u_t(t) \tag{12}$$

where $X_t(t) = \begin{bmatrix} x_t(t) & v_t(t) \end{bmatrix}^T$ and $u_t(t) = \begin{bmatrix} f_h(t) & f_e(t) \end{bmatrix}^T$. The actual forms of the state-space matrices are omitted for brevity.

In the adaptive control framework used in this paper, all the input and all the output channels must have the same amount of latency. Therefore, the master measurements and the master control action in Fig. 1 are padded by $\tau_1(t)$ and $\tau_2(t)$ delay, respectively. Since the system dynamics has been locally linearized, the delay in the output measurement channels can be relocated to the input channels resulting in a system with $d(t) = \tau_1(t) + \tau_2(t)$ delay in all of the control signals.

The states of the combined master, slave, and tool system are defined as follows

$$X(t) = \begin{bmatrix} X_s(t) & \alpha_p X_s(t) - X_m(t) & X_m(t) - X_t(t) \end{bmatrix}^T \quad (13)$$

where $X_m(t)$, $X_s(t)$, and $X_t(t)$ have been introduced in (10), (11) and (12); α_f and α_p have been defined in (7) and (8). The position tracking errors between the master and slave, and the master and virtual tool are included in the state vector. The transparency objectives in (7)-(9) can be enforced by regulating these tracking errors to zero. The evolution of the system states defined in (13) is governed by

$$\begin{aligned} \dot{X}(t) &= AX(t) + Bu(t - d(t)) + B_{f_h^*} f_h^* \\ u(t) &= \begin{bmatrix} f_{cs}(t) & f_{cm}(t) \end{bmatrix}^T \end{aligned} \quad (14)$$

It is straightforward to obtain the system matrices, A and B, from A_m, B_m, A_s, B_s, A_t, and B_t.

For notational convenience, the argument of the control action in (14) is defined as

$$m(t) \triangleq t - d(t) \quad (15)$$

It is assumed that the argument function is always increasing by time, i.e. $\dot{m}(t) = 1 - \dot{d}(t) > 0$, which leads to the following constraint on the time-varying time delay

$$\dot{d}(t) < 1 \quad (16)$$

Finally the inverse of the function $m(\cdot)$, which is also a function itself, can be found as

$$q(m(t)) = t \quad (17)$$

IV. Delay Reduction and Model-Based State Prediction

In our earlier paper [1] which was inspired by the work of [14], a new delay reduction technique was proposed which can be applied to an uncertain multi-input/multi-output system with a constant known time delay. In this paper a new version of the reduction is introduced which can be applied to systems with known but varying time delay. In this case the system dynamics are governed by

$$\dot{X}(t) = AX(t) + Bu(t - d(t)) \quad (18)$$

The delay-reduced state is defined as

$$\hat{Z}(t) \triangleq \bar{X}(t) + \int_{m(t)}^{t} \hat{\Phi}(t, q(s))\dot{q}(s)\hat{B}(s)u(s)ds \quad (19)$$

where $m(\cdot)$ and $q(\cdot)$ have already been defined in (15) and (17) and

$$\begin{aligned} \dot{\bar{X}}(t) &= \hat{A}(m(t))\bar{X}(t) + \dot{q}(m(t))\hat{B}(m(t))u(m(t)) \\ &\quad + L(t)\underbrace{(X(t) - \bar{X}(t))}_{e(t)} \end{aligned} \quad (20)$$

By applying the new reduction method to the teleoperation system defined in (14), one can write

$$\begin{aligned} \hat{Z}(t) &= \bar{X}(t) + \int_{m(t)}^{t} \hat{\Phi}(t, q(s))\dot{q}(s)\hat{B}(s)u(s)ds \\ &\quad + \int_{m(t)}^{t} \hat{\Phi}(t, q(s))\dot{q}(s)\hat{Bf_h^*}(s)ds \end{aligned} \quad (21)$$

$$\begin{aligned} \dot{\bar{X}}(t) &= \hat{A}(m(t))\bar{X}(t) + \dot{q}(m(t))\hat{B}(m(t))u(m(t)) \\ &\quad + \dot{q}(m(t))\hat{Bf_h^*}(m(t)) + L(t)\underbrace{(X(t) - \bar{X}(t))}_{e(t)} \end{aligned} \quad (22)$$

where $\hat{Bf_h^*}$ is an estimation of $B_{f_h^*} f_h^*$. Note that (21) and (22) use the estimated values of the system parameters the calculation of which will be discussed in the following section.

The dynamics of the reduced system can be computed by finding the derivative of $\hat{Z}(t)$ in (21), by using the Leibniz integral rule [18] and by substituting $\dot{\bar{X}}$ from (22) as

$$\begin{aligned} \dot{\hat{Z}}(t) &= \hat{A}(m(t))\hat{Z}(t) + \hat{\Phi}(t, q(t))\dot{q}(t)\hat{B}(t)u(t) \\ &\quad + \hat{\Phi}(t, q(t))\dot{q}(t)\hat{Bf_h^*}(t) + L(t)e(t) \end{aligned} \quad (23)$$

The predicted state of the system in future, $\hat{X}(q(t))$, is calculated from the reduced state, $\hat{Z}(t)$, using the following equation

$$\hat{X}(q(t)) = \hat{\Phi}(q(t), t)\hat{Z}(t) \quad (24)$$

The estimated system transition matrix, $\hat{\Phi}(t,s)$, satisfies

$$\frac{\partial \hat{\Phi}(t,s)}{\partial t} = \hat{A}(m(t))\hat{\Phi}(t,s) \quad , \quad \hat{\Phi}(s,s) = I \quad (25)$$

Using (25), the dynamics of the predicted state can be calculated as

$$\begin{aligned} \dot{\hat{X}}(q(t)) &= \dot{q}(t)\hat{A}(t)\hat{X}(q(t)) + \dot{q}(t)\hat{B}(t)u(t) + \dot{q}(t)\hat{Bf_h^*}(t) \\ &\quad + \hat{\Phi}(q(t), t)L(t)e(t) \end{aligned} \quad (26)$$

V. Teleoperation Performance and Stability

The proposed reduction method removes the delay from the system and results in the delay-free dynamics of the predicted state in (26). To achieve the transparency objectives in (8) and (9), the following outputs are defined based on partial states and will be regulated to zero.

$$y_1(t) \triangleq \hat{X}_4(q(t)) + \lambda \hat{X}_3(q(t)) \quad (27)$$

$$y_2(t) \triangleq \hat{X}_6(q(t)) + \lambda \hat{X}_5(q(t)) \quad (28)$$

In these definitions, $\hat{X}_i(q(t))$ is the ith element of the predicted state defined by the dynamics in (26). Using these dynamics, the system outputs can be rewritten as

$$y_1(t) = \dot{\hat{X}}_3(q(t)) + \lambda \hat{X}_3(q(t)) - \hat{\Phi}_3(q(t), t)L(t)e(t) \quad (29)$$

$$y_2(t) = \dot{\hat{X}}_5(q(t)) + \lambda \hat{X}_5(q(t)) - \hat{\Phi}_5(q(t), t)L(t)e(t) \quad (30)$$

If $y_1(t)$ and $y_2(t)$ are regulated to zero and provided that $e(t) \rightarrow 0$, one can write

$$\dot{\hat{X}}_3(q(t)) \to 0, \quad \hat{X}_3(q(t)) \to 0 \tag{31}$$

$$\dot{\hat{X}}_5(q(t)) \to 0, \quad \hat{X}_5(q(t)) \to 0 \tag{32}$$

From (31) and (32) it can be concluded that the transparency objectives in (8) and (9) are achieved.

To find the output regulating control action, $u(t)$, the derivative of the defined outputs in (27) and (28) should be calculated using the dynamics of the predicted state in (26), i.e.

$$\dot{y}(t) = \begin{pmatrix} \dot{y}_1(t) \\ \dot{y}_2(t) \end{pmatrix} = \dot{q}(t)\left[\begin{pmatrix} \hat{A}_4(t) \\ \hat{A}_6(t) \end{pmatrix}\hat{X}(q(t)) + \begin{pmatrix} \hat{B}_4(t) \\ \hat{B}_6(t) \end{pmatrix}u(t) + \begin{pmatrix} \hat{Bf^*_h}_4(t) \\ \hat{Bf^*_h}_6(t) \end{pmatrix} + \begin{pmatrix} \lambda\hat{X}_4(q(t)) \\ \lambda\hat{X}_6(q(t)) \end{pmatrix}\right] + \begin{pmatrix} \hat{\Phi}_4(q(t),t) + \lambda\hat{\Phi}_3(q(t),t) \\ \hat{\Phi}_6(q(t),t) + \lambda\hat{\Phi}_5(q(t),t) \end{pmatrix}L(t)e(t) \tag{33}$$

where the index i for a matrix or a vector represents the ith row of the corresponding matrix or vector. The desired closed-loop dynamics for the outputs are defined as

$$\dot{y}(t) \quad = \quad \Omega y(t) \quad , \qquad \Omega = \text{diag}\,(-\lambda_1 \quad -\lambda_2) \tag{34}$$

where λ_1 and λ_2 are positive scalars. Now using (33) and (34), the control action $u(t)$ can be calculated based on the parameter estimates and the sensor measurements as

$$u(t) = \begin{pmatrix} \hat{B}_4(t) \\ \hat{B}_6(t) \end{pmatrix}^{-1}\left[\frac{1}{\dot{q}(t)}\Omega y(t) - \begin{pmatrix} \hat{A}_4(t) \\ \hat{A}_6(t) \end{pmatrix}\hat{X}(q(t)) - \begin{pmatrix} \lambda\hat{X}_4(q(t)) \\ \lambda\hat{X}_6(q(t)) \end{pmatrix} - \begin{pmatrix} \hat{Bf^*_h}_4(t) \\ \hat{Bf^*_h}_6(t) \end{pmatrix} - \frac{1}{\dot{q}(t)}\begin{pmatrix} \hat{\Phi}_4(q(t),t) + \lambda\hat{\Phi}_3(q(t),t) \\ \hat{\Phi}_6(q(t),t) + \lambda\hat{\Phi}_5(q(t),t) \end{pmatrix}L(t)e(t)\right] \tag{35}$$

This completes the derivation of the control action. Combining (15)-(17) ensures that $\dot{q}(t)$ is always non-zero and therefore its inverse in (35) exists. The next step is proving the stability of the system and deriving the parameter adaptation law.

The dynamics of the state observation error, $e(t)$ as defined in (22), can be obtained by taking the derivative of $e(t)$ and substituting $\dot{X}(t)$ and $\dot{\hat{X}}(t)$ from (14) and (22), respectively.

$$\dot{e}(t) = \left(\hat{A}(m(t)) - L(t)\right)e(t) + \tilde{A}(m(t))X(t) + \left(B - \dot{q}(m(t))\hat{B}(m(t))\right)u(m(t)) + \left(B_{f^*_h}f^*_h - \dot{q}(m(t))\hat{Bf^*_h}(m(t))\right) \tag{36}$$

Here $\tilde{A} \triangleq A - \hat{A}$ is the estimation error of the matrix A. The user-defined observer gain $L(t)$ is chosen to be

$$L(t) = \hat{A}(m(t)) - \Upsilon \tag{37}$$

where $\Upsilon < 0$ is a constant matrix. Replacing $L(t)$ from (37) in (36) results in the following observer error dynamics

$$\dot{e}(t) = \Upsilon e(t) + \tilde{A}(m(t))X(t) + \left(B - \dot{q}(m(t))\hat{B}(m(t))\right)u(m(t)) + \left(B_{f^*_h}f^*_h - \dot{q}(m(t))\hat{Bf^*_h}(m(t))\right) \tag{38}$$

To remove the delay from the estimation error terms a new signal, $w(t)$, is defined based on the following dynamics

$$\dot{w}(t) = \Upsilon w(t) - \left[\left(\hat{A}(t) - \hat{A}(m(t))\right)X(t) + \left(\hat{B}(t) - \dot{q}(m(t))\hat{B}(m(t))\right)u(m(t)) + \left(\hat{Bf^*_h}(t) - \dot{q}(m(t))\hat{Bf^*_h}(m(t))\right)\right] \tag{39}$$

The signal $w(t)$ will be added to the error signal $e(t)$ resulting in the definition of a new variable, i.e. $r(t) \triangleq e(t) + w(t)$. Now using (36) and (39), the dynamics of $r(t)$ can be obtained as

$$\dot{r}(t) = \Upsilon r(t) + \tilde{A}(t)X(t) + \tilde{B}(t)u(m(t)) + \tilde{Bf^*_h}(t) \tag{40}$$

$$\tilde{B} = B - \hat{B}, \quad \tilde{Bf^*_h} = B_{f^*_h}f^*_h - \hat{Bf^*_h} \tag{41}$$

To facilitate the use of adaptive control, the dynamics of $r(t)$ in (40) are rewritten in an equivalent linear-in-parameter form. The details of these calculations are omitted in the interest of space.

$$\dot{r}(t) = \Upsilon r(t) + Y(t)\tilde{\theta}(t) \tag{42}$$

Here, $Y(t)$ is a regression matrix that is a function of the measurements and $\tilde{\theta}(t)$ is the vector of parameter estimation errors.

A Lyapunov analysis can now be employed to prove the stability of the observation error and to find the parameter adaptation law. Consider the following candidate Lyapunov function:

$$V(t) = r^T(t)Pr(t) + \tilde{\theta}^T(t)\Gamma^{-1}\tilde{\theta}(t) \tag{43}$$

where $P = P^T > 0$ and $\Gamma = \Gamma^T > 0$. The derivative of $V(t)$ along the system state trajectory can be computed using the dynamics of $r(t)$ in (42) as

$$\dot{V}(t) = r^T(t)\left(\Upsilon^T P + P\Upsilon\right)r(t) + 2r^T(t)PY(t)\tilde{\theta}(t) + 2\dot{\tilde{\theta}}^T(t)\Gamma^{-1}\tilde{\theta}(t) \tag{44}$$

Now assuming that the actual parameters vector θ is constant, the following projection-based adaptation law is used

$$\dot{\hat{\theta}}(t) = -\dot{\tilde{\theta}}_i(t) = \begin{cases} 0 & \hat{\theta} \le \theta_i^- \\ \Gamma^T Y^T(t)P^T r(t) & \theta_i^- \le \hat{\theta} \le \theta_i^+ \\ 0 & \theta_i^+ \le \hat{\theta} \end{cases} \tag{45}$$

where θ_i^- and θ_i^+ are a priori known lower and upper bounds for the corresponding parameter. It can be shown that using this adaption law yields

$$2r^T(t)PY(t)\tilde{\theta}(t) + 2\dot{\tilde{\theta}}^T(t)\Gamma^{-1}\tilde{\theta}(t) \le 0 \tag{46}$$

According to [19], for a matrix $\Upsilon < 0$ and any arbitrary matrix $Q < 0$ there exists a matrix $P > 0$ such that

$$\Upsilon^T P + P\Upsilon = Q < 0 \tag{47}$$

Substituting (46) and (47) in the derivative of the Lyapunov function in (44) results in the following

$$\dot{V}(t) = r^T(t)Qr(t) \le 0 \tag{48}$$

From (43) and (48), it can be concluded that $r(t)$ belongs to $L_2 \bigcap L_\infty$. $\ddot{V}$ can also be shown to be bounded. Using the boundedness of $\ddot{V}$ and (43) and by employing the Barbalat's Lemma [20] it can be proven that the signal $r(t)$ converges to zero. It is also straightforward to show the convergence of the signal $e(t)$ and the tracking errors in (31) and (32) to zero. Details are omitted due to lack of space.

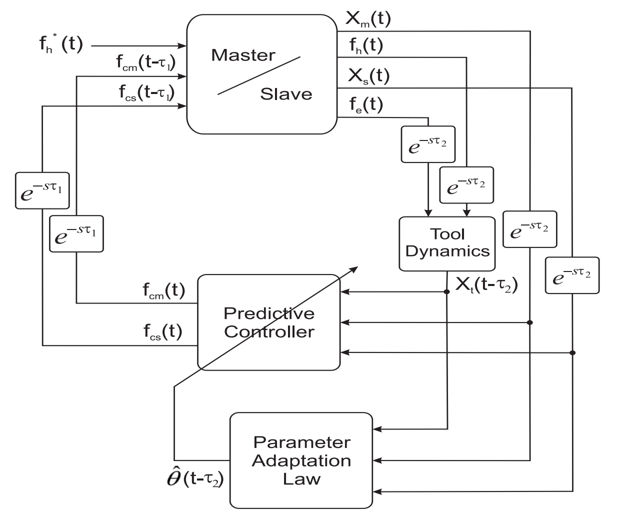

Fig. 2. Time-delay teleoperation system with the proposed adaptive predictive controller

VI. Design Example and Simulation Results

Fig. 2 shows the schematic of the proposed adaptive predictive controller for time-varying delayed teleoperation system. The slave control action and measurements are subject to time-varying delays $\tau_1(t)$ and $\tau_2(t)$. Delayed hand and environment force signals are used to generate delayed virtual tool position and velocity. These synthesized observations, along with the actual observations, enter the model-based predictive controller block at the master site which produces the control signals. Estimated model of the system is updated using the measurements and the parameter adaptation law.

The proposed adaptive controller is applied to a linear single-axis time-delay teleoperation system involving two similar masses. Since the master and slave dynamics are already linear, the adaptive feedback linearizing controller is not needed in this example. It is assumed that the operator manipulates the slave robot in free motion and in contact with an environment with unknown stiffness. The system and controller parameters used in the simulations are presented in Table I. It should be noted that the model parameters are only used for simulating the system response and their values are not available to the controller. The variable round-trip time delay used in the simulations is $d(t) = 0.1 - 0.1\cos(\pi t/10)$. This delay satisfies the condition in (16).

Fig. 3 illustrates the responses of the proposed controller with the time-varying time delay mentioned above. In free motion, the operator would feel the dynamics of the virtual tool as evident by the non-zero hand force observed in the free motion portions of Fig. 3(b). The positions of master, slave, and virtual tool closely follow each other in free motion which confirms that the performance objectives in (8) and (9) are both achieved with good accuracy. At $t \simeq 20$sec, the slave makes contact with the environment which triggers the controller to adapt to this change in system parameters. During the course of the contact, the environment and hand forces as well as the master and slave positions closely track each other as can be seen in Fig. 3. This

System Parameters	
Master	$m_m = 1$ kg $b_m = 1$ N.s/m $k_m = 0$ N/m
Arm	$m_h = 0.35$ kg $b_h = 5$ N.s/m $k_h = 5$ N/m
Slave	$m_s = 1$ kg $b_s = 1$ N.s/m $k_s = 0$ N/m
Environment	$m_e = 0$ kg $b_e = 10$ N.s/m $k_e = 1000$ N/m
Tool	$m_t = 1$ kg $b_t = 1$ N.s/m $k_t = 1$ N/m
Controller Parameters	
$\Omega = \text{diag}(-50,-50), \Upsilon = \text{diag}(-50,-50,-50,-50,-50,-50)$	
$P = \text{diag}(10,10,10,10,10,10),\quad \lambda_1 = \lambda_2 = 50$	

TABLE I

System and controller parameters.

demonstrates that the tracking objectives in (8) and (9) are accurately achieved throughout the contact. As Fig. 3 shows, the controller provides a stable transition from free motion to contact with the environment. The changes in the contact forces are deliberately made by the operator to show the tracking performance of the controller.

The simulations were also repeated using the controller in [1] which uses a constant time delay. Delay values of of 20, 100 and 200 msec were employed. The results in Figs. 4, 5 and 6 show that the constant delay controller could become unstable if the actual delay is time-varying. In such cases, the new controller must be employed.

VII. Conclusions and Future Work

In this paper, a *provably stable* adaptive model-based predictive controller was proposed for variable time-delay teleoperation. The controller uses available information about system model and time delay to improve the transparency of teleoperation while maintaining its stability. A revised delay reduction method was developed that utilizes estimated model parameters and an auxiliary state observer. The teleoperation performance objectives, i.e. non-delayed virtual tool impedance shaping and position tracking were achieved within an output-regulation control framework and using the reduced dynamics. The stability of the system was proven using a Lyapunov analysis which also generated the parameters adaptation law. The effectiveness of the proposed controller was demonstrated in numerical simulations of a single-axis time delay teleoperation system. In particular, while our earlier controller with constant delay in [1] became unstable under time-varying communication delay, the

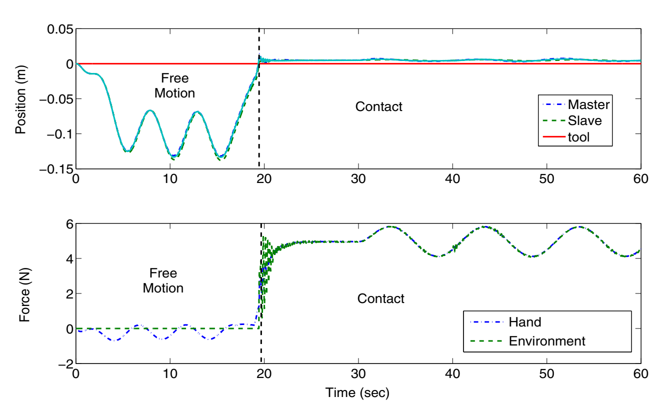

Fig. 3. The new model-based adaptive controller with time-varying delay: (a) position tracking and (b) force tracking.

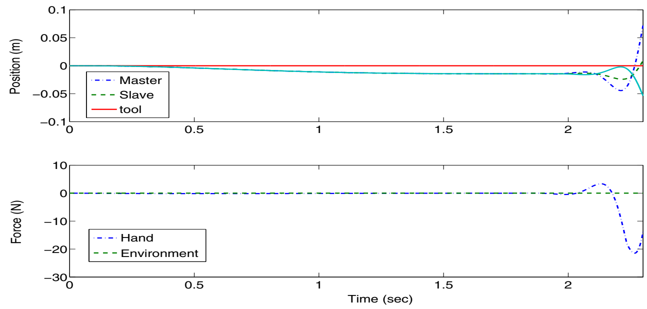

Fig. 4. Model-based adaptive controller in [1] with 20 msec constant delay in design: (a) position tracking and (b) force tracking; simulation stopped due to instability.

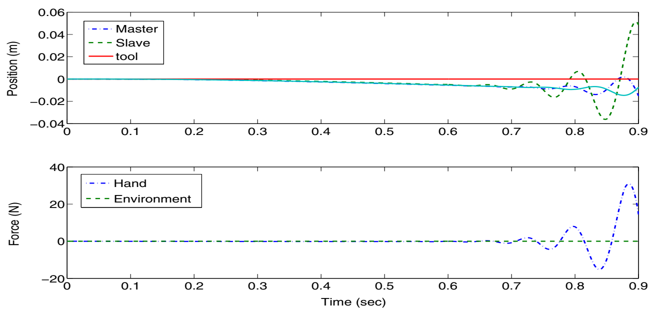

Fig. 5. Model-based adaptive controller in [1] with 100 msec constant delay in design: (a) position tracking and (b) force tracking; simulation stopped due to instability.

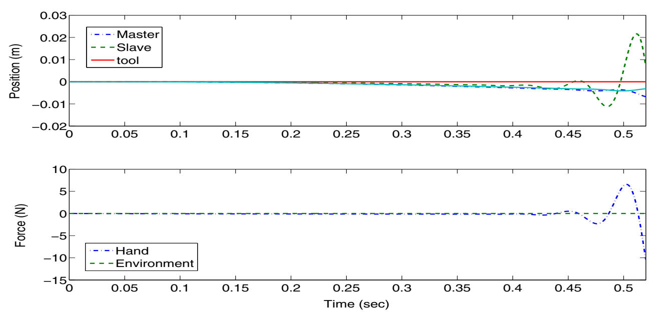

Fig. 6. Model-based adaptive controller in [1] with 200 msec constant delay in design: (a) position tracking and (b) force tracking; simulation stopped due to instability.

new controller remained stable and exhibited an excellent performance.

It should be noted that perfectly delay-free transparent response can only be achieved under constant user and environment parameters, including a constant user exogenous force. Changes in these parameters may generate a transient error which would be corrected by the controller. The decay rate of these transient errors can be increased by increasing the adaptation gains. However, these gains can not be increased indefinitely due to the effect of measurement noise and sampling on system performance and stability.

Immediate future work involves an experimental verification of the proposed controller. In this paper it was assumed that a model of time delay is available in the form of $m(t)$ in (15), satisfying the condition in (16). In practice such model can be easily constructed from a real-time measurement of the round-trip delay. In a packet-switched network such as the Internet the condition in (16) can be satisfied by carefully handling the data packets. For example in the case of an increasing delay, there would be periods of information black-out during which old measurements could be buffered and used for control. When the delay is decreasing multiple packets may arrive within one sample time in which case all but the most recent packet may be discarded. Investigating the stability of such strategy is not trivial and remains for future work. Research must also be carried out to modify the controller so it would not require any extra delay padding of the signals.

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