Research Article

Adaptive Control of Delayed Teleoperation Systems with Parameter Convergence

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It is well known that parameter convergence in adaptive control can bring about an improvement of system performance, including accurate online identification, exponential tracking, and robust adaptation without parameter drift. However, strong persistent-excitation (PE) or sufficient-excitement (SE) conditions should be satisfied to guarantee parameter convergence in the classical adaptive control. This paper proposes a novel adaptive control to guarantee parameter convergence without PE and SE conditions for nonlinear teleoperation systems with dynamic uncertainties and time-varying communication delays. The stability criterion of the closed-loop teleoperation system is given in terms of linear matrix inequalities. The effectiveness of this approach is illustrated by simulation studies, where both master and slave are assumed to be two-link manipulators with full nonlinear system dynamics.

1. Introduction

Bilateral teleoperation systems are one of the most well-known time-delay systems which allow a human operator to extend his/her intelligence and manipulation skills to the remote environments. A typical teleoperation system is composed of five parts: human operator, master, communication channel, slave, and task environment. The master is directly handled by a human operator to manipulate the slave in the task environment, and the signals (position, velocity, or interaction force) from the slave are sent back to the master to improve the performance. Recent years have witnessed considerable advances in the control studies of teleoperation systems, owing to their broad engineering applications in telesurgery, space exploration, nuclear operation, undersea exploration, and so forth.

It is well known that the information between the master and slave robots is transmitted via a communication network, and long-distance data transmission generally causes communication time delays. The existence of such communication time delays may affect the stability and the control performance of teleoperation systems. In order to solve this problem, a variety of control schemes have been proposed in the literature. The breakthrough work on bilateral teleoperation problem was achieved in [1], in which the concepts from

network theory, passivity, and scattering theory were used to analyze the stability of the controlled teleoperation systems [2], and then the master-slave synchronization and stability analysis of teleoperation systems with various kinds of time delays, such as constant delays [1], time-varying delays [3–8], or stochastic delays [9–11], have been hot topics in the study of teleoperation systems.

Another typical concern for teleoperation systems is the dynamic uncertainties. For model-based controllers, the system parameters are assumed to be explicitly known. However, it is unrealistic to accurately get the system model in practical applications. Therefore, one of the main solutions to reduce the influence of uncertainty on the performance of a teleoperation system is to design an adaptive controller. For nonlinear teleoperation systems, the design of adaptive controllers mainly uses a basic fact: the master-slave robots are linearly parameterized [12]. In [13], an adaptive controller for teleoperators with time delays, which ensures synchronization of positions and velocities of the master and slave manipulators and does not rely on the use of the ubiquitous scattering transformation, was proposed. Based on [13], two versions of adaptive controllers for nonlinear bilateral teleoperators were proposed in [5]. The authors in [14] proposed a novel adaptive control framework for

nonlinear teleoperation systems with dynamic and kinematic uncertainties and time-varying time delays. Unfortunately, one of the drawbacks of adaptive controllers proposed in [5, 13, 14] is that the parameter estimates are not guaranteed to converge to the true parameters. It is well known that the convergence of the parameters to their true values can improve system performance with accurate online identification, exponential tracking, and robust adaptation without parameter drift. Unfortunately, these features are not guaranteed unless a condition of persistent excitation (PE) is satisfied [15]. However, the PE condition is very stringent and often infeasible in practical control systems [16]. Hence, some improved methods which relax the condition of PE should be proposed.

Motivated by the above concerns, in this paper, a new adaptive controller is designed for teleoperation systems with time-varying delays, and the convergence of parameters to their true values is achieved, which then gives rise to an improvement of system performance. A new prediction error is designed to guarantee the parameter convergence, and the condition of PE is not required; thus, the proposed control scheme is more practical in real applications.

The arrangement of this paper is as follows. In Section 2, the system modeling and some preliminaries are given. In Section 3, the adaptive control with parameter convergence is given and its stability is analyzed in Section 4. A simple teleoperation system composed of two robots with two degrees of freedom is given as an example to show the effectiveness of the proposed method in Section 5. Finally, the summary and conclusion of this paper are given in Section 6.

Notations. Throughout this paper, the superscript T stands for matrix transposition. $\mathbb{R}^n$ denotes the n -dimensional Euclidean space with vector norm $\|\cdot\|$. $\mathbb{R}^{n \times m}$ is the set of all $n \times m$ real matrices. $*$ represents a block matrix which is readily referred by symmetry. $\lambda_{\min}(M)$ and $\lambda_{\max}(M)$ denote the maximum and the minimum eigenvalue of matrix $M = M^T \in \mathbb{R}^{n \times n}$, respectively. For any function $f: [0, \infty) \rightarrow \mathbb{R}^n$, the $\mathcal{L}_\infty$ -norm is defined as $\|f\|_\infty := \sup_{t \geq 0} |f(t)|$, and the square of the $\mathcal{L}_2$ -norm is defined as $\|f\|_2^2 := \int_0^\infty |f(t)|^2 dt$. The $\mathcal{L}_\infty$ and $\mathcal{L}_2$ spaces are defined as the sets $\{f: [0, \infty) \rightarrow \mathbb{R}^n, \|f\|_\infty < \infty\}$ and $\{f: [0, \infty) \rightarrow \mathbb{R}^n, \|f\|_2 < \infty\}$, respectively.

2. Problem Formulation and Preliminaries

Consider teleoperation systems described as follows:

$$\begin{aligned} M_m(q_m) \ddot{q}_m + C_m(q_m, \dot{q}_m) \dot{q}_m + G_m(q_m) &= F_m + \tau_m \\ M_s(q_s) \ddot{q}_s + C_s(q_s, \dot{q}_s) \dot{q}_s + G_s(q_s) &= F_s + \tau_s, \end{aligned} \quad (1)$$

where $q_i, \dot{q}_i, \ddot{q}_i \in \mathbb{R}^n$ are the vectors of the joint position, velocity, and acceleration with $i = m$ or s representing the master or the slave robot manipulator, respectively. Similarly, M_i represents the mass matrix, and $C_i(q_i, \dot{q}_i)$ embodies the Coriolis and centrifugal effects. τ_i is the control force, and finally F_m, F_s are the external forces applied to the manipulator end-effectors. Each robot in (1) satisfies the structural

properties of robotic systems, that is, the following properties [2, 12]:

- (P1) The inertia matrix $M_i(q_i)$ is a symmetric positive-definite function and is lower and upper bounded; that is, $0 < \rho_i^m I \leq M_i(q_i) \leq \rho_i^M I < \infty$, where ρ_i^m, ρ_i^M are positive scalars.
- (P2) The matrix $\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)$ is skew symmetric.
- (P3) For all $q_i, x, y \in \mathbb{R}^{n \times 1}$, there exists a positive scalar c_i such that $\|C_i(q_i, x)y\| \leq c_i \|x\| \|y\|$.
- (P4) The equations of motion of n -link robot can be linearly parameterized as

$$\begin{aligned} M_i(q_i) \ddot{q}_i + C_i(q_i, \dot{q}_i) \dot{q}_i + G_i(q_i) &= Y_{io}(q_i, \dot{q}_i, \ddot{q}_i) \theta \\ &\triangleq y_i, \end{aligned} \quad (2)$$

where $Y_{io}(q_i, \dot{q}_i, \ddot{q}_i) \triangleq Y_{io} \in \mathbb{R}^{n \times n_i}$ is a matrix of known functions called regressor and $\theta_i \in \mathbb{R}^{n_i}$ is a vector of unknown parameters.

In this paper, the data is transmitted from the master to the slave and from the slave to the master over delayed communication with variable delays. The communication delays are assumed to have certain bounds, which is precisely stated in Assumption 1.

Assumption 1. For each $i = m, s$, the variable communication time delay $T_i(t)$ has a known upper bound $h_i(t)$; that is, $0 \leq T_i(t) \leq h_i$. Additionally, the time derivative $\dot{T}_i$ is bounded.

3. Adaptive Control Design

Suppose the positions of the master and the slave are available for measurement and are transmitted through the delayed network communication. Let $e_i \in \mathbb{R}^n$ denote the position errors by

$$\begin{aligned} e_m &\triangleq q_m - q_s(t - T_s(t)) \\ e_s &\triangleq q_s - q_m(t - T_m(t)). \end{aligned} \quad (3)$$

We define the following auxiliary variables:

$$\eta_m \triangleq \dot{q}_m + \lambda_m e_m \quad (4)$$

$$\eta_s \triangleq \dot{q}_s + \lambda_s e_s, \quad (5)$$

where λ_m, λ_s are positive constants. Using property (P4), letting $Y_i \theta_i = Y_i(q_i, \dot{q}_i, e_i, \dot{e}_i) \theta_i = M_i(q_i) \lambda_i \dot{e}_i + C_i(q_i, \dot{q}_i) \lambda_i e_i - G_i(q_i)$, $i \in \{m, s\}$, the following control laws for the master and the slave are proposed:

$$\begin{aligned} \tau_m &= -Y_m \hat{\theta}_m - K_m \eta_m \\ \tau_s &= -Y_s \hat{\theta}_s - K_s \eta_s, \end{aligned} \quad (6)$$

where $\hat{\theta}_i$ is the estimate of θ_i , $K_i > 0$.

Substituting the control law (6) into the teleoperation dynamics (1), we obtain the following dynamics for $t > 0$:

$$M_m(q_m) \dot{\eta}_m + C_m(q_m, \dot{q}_m) \eta_m + K_m \eta_m = Y_m \tilde{\theta}_m + F_m \quad (7)$$

$$M_s(q_s) \dot{\eta}_s + C_s(q_s, \dot{q}_s) \eta_s + K_s \eta_s = Y_s \tilde{\theta}_s + F_s,$$

where $\tilde{\theta}_i \triangleq \theta_i - \hat{\theta}_i$.

A straightforward choice of the adaptive law $\dot{\hat{\theta}}_i = \Gamma_i Y_i^T \eta_i$ was first proposed by Slotine and Li [17] and has been widely used in adaptive control of teleoperation systems [2, 5, 13]. However, it is pointed out that this adaptive law cannot guarantee accurate estimations of parameters. In order to achieve convergence of parameters to their true values, the estimation error $\tilde{\theta}_i$ should be introduced into the control design. However, the value of $\tilde{\theta}_i$ is not obtainable since the true value of θ_i is not available, and thus the prediction error $e_{io} = Y_{io} \tilde{\theta}_i$ or its filtered counterpart $e_{iw} = \alpha \int_0^t e^{-\delta(t-v)} e_{io}(v) dv$ is used to improve the tracking performance. However, the use of e_{io} or e_{iw} still needs the PE condition to make the system exponentially stable. In the following, we introduce an auxiliary variable z_i such that $z_i = P_i \tilde{\theta}_i$, where P_i is a designed lower bounded positive-definite matrix, to adaptive control of the teleoperation system. Thus, the following adaptive laws are proposed for the master and the slave:

$$\dot{\hat{\theta}}_i = \Gamma_i (Y_i^T \eta_i + (\xi_i + \delta_i) z_i) \quad (8)$$

$$\begin{aligned} \dot{z}_i &= -\mu_i z_i + Y_{io}^T e_{io} - P_i \dot{\hat{\theta}}_i, \\ z_i(0) &= 0 \end{aligned} \quad (9)$$

$$\begin{aligned} \dot{P}_i &= -\mu_i P_i + Y_{io}^T Y_{io}, \\ P_i(0) &= P_{i0} > 0 \end{aligned} \quad (10)$$

$$\mu_i = \mu_{i0} (1 - \kappa_{i0} \|P_i^{-1}\|), \quad (11)$$

where

$$\begin{aligned} e_{mo} &\triangleq y_m - Y_{mo} \hat{\theta}_m = Y_{mo} \tilde{\theta}_m \\ e_{so} &\triangleq y_s - Y_{so} \hat{\theta}_s = Y_{so} \tilde{\theta}_s, \end{aligned} \quad (12)$$

where κ_{i0} and μ_{i0} are two positive constants specifying the lower bound of the norm of P_i and the maximum forgetting rate [17]; $\Gamma_m \in \mathbb{R}^{n_m \times n_m}$ and $\Gamma_s \in \mathbb{R}^{n_s \times n_s}$ are two constant positive-definite matrices. From (10) and (11), one can show that, $\forall t \geq 0$, $\mu_i \geq 0$, and $P_i \geq \kappa_{i0} I$.

The coefficient ξ_i is given by

$$\xi_i = \alpha_i \frac{\|Y_i^T \eta_i\|}{\kappa_{i0}}, \quad (13)$$

where $\alpha_i > 0$ is a constant.

Remark 2. By (12), it is easy to see that the prediction error e_{io} is related to the regressor Y_i , which requires the information of joint acceleration. To avoid this, the adaptive law ((8)–(11)) with filtered torques and filtered regressor Y_{iw} could be used. The filtered prediction errors of estimated parameters are defined as

$$e_{mw} \triangleq y_{mw} - Y_{mw} \hat{\theta}_m = Y_{mw} \tilde{\theta}_m \quad (14)$$

$$e_{sw} \triangleq y_{sw} - Y_{sw} \hat{\theta}_s = Y_{sw} \tilde{\theta}_s, \quad (15)$$

where y_i is the filtered forces $\tau_i + F_i$, that is,

$$y_{iw} = \alpha \int_0^t e^{-\alpha(t-\delta)} y_i d\delta, \quad (16)$$

and can be calculated without acceleration terms $M_i(q_i) \ddot{q}_i$ by convolving both sides of (2) by a filter $W(s) = \alpha/(s + \alpha)$ [18].

4. Stability Analysis

Denote $x_m = [\eta_m^T, \tilde{\theta}_m^T]^T$, $x_s = [\eta_s^T, \tilde{\theta}_s^T]^T$, and $x = [x_m^T, x_s^T]^T$ and define the new state $x_i(s) \triangleq x(t + s)$, $s \in [-h, 0]$ which take values in $C([-h, 0]; \mathbb{R}^{n+m+s})$, $h = \max\{h_m, h_s\}$.

The following theorem summarizes the main result of this paper.

Theorem 3. Consider the bilateral teleoperation system (1) controlled by (6) together with the updating law ((8)–(11)) under the communication channel satisfying Assumption 1, if there exist positive-definite matrices R_m, R_s such that the following linear matrix inequality (LMI) holds, respectively:

$$\Pi = \begin{bmatrix} \Pi_1 & 0 & 0 & -I \\ * & \Pi_2 & -I & 0 \\ * & * & -\frac{R_m}{h_m} & 0 \\ * & * & * & -\frac{R_s}{h_s} \end{bmatrix} < 0, \quad (17)$$

with

$$\begin{aligned} \Pi_1 &= -\frac{1}{\lambda_m} I + h_m R_m, \\ \Pi_2 &= -\frac{1}{\lambda_s} I + h_s R_s, \end{aligned} \quad (18)$$

and then when the considered teleoperation system is in free motion, that is, $F_m = F_s = 0$, all the signals are bounded and the position errors, velocities, and estimation errors asymptotically converge to zero; that is, $\lim_{t \rightarrow \infty} q_m - q_s = \lim_{t \rightarrow \infty} \dot{q}_m = \lim_{t \rightarrow \infty} \dot{q}_s = \lim_{t \rightarrow \infty} \tilde{\theta}_m = \lim_{t \rightarrow \infty} \tilde{\theta}_s = 0$. Moreover, the estimation errors converge to a specified domain within a given time.

Proof. Define the following function:

$$V_i(x, t) = \frac{1}{2} \eta_i^T M_i(q_i) \eta_i + \frac{1}{2} \tilde{\theta}_i^T \Gamma_i^{-1} \tilde{\theta}_i. \quad (19)$$

It is obvious that V_i is positive-definite and radially unbounded with regard to η_i and $\tilde{\theta}_i$. Using property (P2), the derivative of V_i along the trajectory of system (7) is

$$\begin{aligned} \dot{V}_i(x, t) &= -\eta_i^T K_i \eta_i - \tilde{\theta}_i^T (\xi_i P_i + \delta_i P_i) \tilde{\theta}_i \\ &\leq -\eta_i^T K_i \eta_i - \delta_i \kappa_{i0} \tilde{\theta}_i^T \tilde{\theta}_i \end{aligned} \quad (20)$$

when $F_m \equiv 0$, $F_s \equiv 0$. Since $V_i(x, t) > 0$, $\dot{V}_i(x, t) < 0$, we conclude that $\eta_i, \tilde{\theta}_i \in \mathcal{L}_\infty \cap \mathcal{L}_2$. By the closed-loop dynamics (7)

and properties (P1)–(P4), we have that $\dot{\eta}_i \in \mathcal{L}_\infty$. Thus, by Barbalat's Lemma, one has that $\lim_{t \rightarrow \infty} \eta_i(t) = 0$. Now, we give the following Lyapunov functional:

$$V = V_1 + V_2 + V_3 \quad (21)$$

with

$$\begin{aligned} V_1 &= \frac{1}{k_m \lambda_m} V_m(x, t) + \frac{1}{k_s \lambda_s} V_s(x, t) \\ V_2 &= (q_m - q_s)^T (q_m - q_s) \\ V_3 &= \sum_{i=m,s} \int_{-h_i}^0 \int_{t+\theta}^t \dot{q}_i^T(s) R_i \dot{q}_i(s) ds d\theta, \end{aligned} \quad (22)$$

where $k_i = \lambda_{\min}\{K_i\}$.

When the external forces $F_m \equiv F_s \equiv 0$, by (4), the derivative of V_1 along with the trajectory of system (7) is given by

$$\begin{aligned} \dot{V}_1(x, t) &= \frac{1}{k_m \lambda_m} \dot{V}_m(x, t) + \frac{1}{k_s \lambda_s} \dot{V}_s(x, t) \\ &\leq - \sum_{i=m,s} \left(\frac{\dot{q}_i^T \dot{q}_i}{\lambda_i} + 2e_i^T \dot{q}_i + \lambda_i e_i^T e_i + \frac{\delta_i \kappa_{i0}}{k_i} \tilde{\theta}_i^T \tilde{\theta}_i \right). \end{aligned} \quad (23)$$

It is noted that the position error $e \triangleq q_m - q_s$ can be expressed as

$$e = e_m - L_s = -e_s + L_m, \quad (24)$$

where $L_m = \int_{t-T_m(t)}^t \dot{q}_m(s) ds$ and $L_s = \int_{t-T_s(t)}^t \dot{q}_s(s) ds$, and hence the time derivative of V_2 along with the trajectory of system (7) is given by

$$\dot{V}_2 = 2(e_m - L_s)^T \dot{q}_m + 2(e_s - L_m)^T \dot{q}_s. \quad (25)$$

Calculating the time derivative of V_3 , one has that

$$\begin{aligned} \dot{V}_3 &= \sum_{i=m,s} h_i \dot{q}_i^T R_i \dot{q}_i - \int_{t-h_i}^t \dot{q}_i^T(s) R_i \dot{q}_i(s) ds \\ &\leq \sum_{i=m,s} h_i \dot{q}_i^T R_i \dot{q}_i - \int_{t-T_i(t)}^t \dot{q}_i^T(s) R_i \dot{q}_i(s) ds \\ &\leq \sum_{i=m,s} h_i \dot{q}_i^T R_i \dot{q}_i - \frac{1}{h_i} L_i R_i L_i \end{aligned} \quad (26)$$

by Jensen's inequality.

Thus, we have

$$\dot{V} = \sum_{i=1,2,3} \dot{V}_i \leq -\xi \Pi \xi - \sum_{i=m,s} \left(\frac{\delta_i \kappa_{i0}}{k_i \lambda_i} |\tilde{\theta}_i|^2 + \lambda_i e_i^T e_i \right), \quad (27)$$

where $\xi = \text{col}\{\dot{q}_m, \dot{q}_s, L_m, L_s\}$ and Π is given in (17).

By (17), we have that $\dot{V} < 0$ and $V > 0$. Furthermore, by (21) and (27), one has that $e_i \in \mathcal{L}_2 \cap \mathcal{L}_\infty$, $\tilde{\theta}_i \in \mathcal{L}_2 \cap \mathcal{L}_\infty$. Thus, by (3), one has that $\dot{e}_m, \dot{e}_s \in \mathcal{L}_\infty$ if the time derivatives

of the communication delays $\dot{T}_i$ are bounded. Now, invoking Barbalat's Lemma, we conclude that $\lim_{t \rightarrow \infty} e_i(t) = 0$. Thus, it is followed by $\lim_{t \rightarrow \infty} \dot{q}_i(t) = 0$ since $\eta_i \rightarrow 0$ as $t \rightarrow \infty$. Since $e = e_m - L_s = -e_s + L_m$, we further conclude that $e \rightarrow 0$ as $t \rightarrow \infty$.

Now, we show that the parameter estimation error $\tilde{\theta}_i$ approaches zero as $t \rightarrow \infty$. Note that the parameter adaption law (8) can be represented as

$$\dot{\tilde{\theta}}_i = -\Gamma_i (Y_i^T \eta_i + (\xi_i + \delta_i) P_i \tilde{\theta}_i) \in \mathcal{L}_\infty \quad (28)$$

Similarly, the conclusion that $\lim_{t \rightarrow \infty} \tilde{\theta}_i(t) = 0$ is guaranteed using Barbalat's Lemma.

To illustrate the transient performance of the teleoperators, we start from the convergence of estimation errors $\tilde{\theta}_i$. Obviously, the Lyapunov candidate function for $\tilde{\theta}_i$ is $\sum_{i=m,s} (1/k_i \lambda_i) \tilde{\theta}_i^T \Gamma_i^{-1} \tilde{\theta}_i$, which we denoted as $V_\theta(t)$. The time derivative of V_θ is given by

$$\begin{aligned} \dot{V}_\theta(t) &= \sum_{i=m,s} \frac{1}{k_i \lambda_i} \tilde{\theta}_i^T \Gamma_i^{-1} \dot{\tilde{\theta}}_i \\ &\leq \sum_{i=m,s} \frac{1}{k_i \lambda_i} (-\tilde{\theta}_i^T Y_i^T \eta_i - \tilde{\theta}_i^T \alpha_i \|Y_i^T \eta_i\| \|\tilde{\theta}_i - \delta_i \kappa_{i0} \tilde{\theta}_i\|) \\ &\leq \sum_{i=m,s} \frac{1}{k_i \lambda_i} ((1 - \alpha_i \|\tilde{\theta}_i\|) \|Y_i^T \eta_i\| \|\tilde{\theta}_i\| - \delta_i \kappa_{i0} \|\tilde{\theta}_i\|^2). \end{aligned} \quad (29)$$

Thus, if $\|\tilde{\theta}_i\| \geq 1/\alpha_i$ for both $i = m, s$, we have $\dot{V}_\theta(t) \leq -\sum_{i=m,s} (\delta_i \kappa_{i0}/k_i \lambda_i) \|\tilde{\theta}_i\|^2 \leq -\delta \|\tilde{\theta}\|^2$, where $\delta = \min\{\delta_m \kappa_{m0}/k_m \lambda_m, \delta_s \kappa_{s0}/k_s \lambda_s\}$. This implies that $\dot{V}_\theta$ is always negative when $\|\tilde{\theta}\| \geq \sqrt{2}/\alpha$ with $\alpha = \min\{\alpha_m, \alpha_s\}$. So, the parameter error $\tilde{\theta}(t) = \text{col}\{\tilde{\theta}_m, \tilde{\theta}_s\}$ will converge to a sphere $\Omega_\theta = \{\tilde{\theta} : \|\tilde{\theta}\| \leq \sqrt{2\lambda_M^\theta \nu_M / \lambda_m^\theta \nu_m / \alpha}\}$, where $\lambda_m^\theta = \min\{\lambda_{\min}(\Gamma_m^{-1}), \lambda_{\min}(\Gamma_s^{-1})\}$, $\lambda_M^\theta = \max\{\lambda_{\max}(\Gamma_m^{-1}), \lambda_{\max}(\Gamma_s^{-1})\}$, $\nu_m = \min\{1/k_m \lambda_m, 1/k_m \lambda_m\}$, and $\nu_M = \max\{1/k_m \lambda_m, 1/k_m \lambda_m\}$ within a given time. $\square$

Remark 4. Compared to the existing works [5, 13, 19], the proposed control scheme guarantees the convergence of parameters to their true values, while the condition of PE is not required. This is accomplished by the boundedness of the matrix P_i in the new-defined prediction error z_i .

5. Simulations

In this section, the simulation results are shown to verify the effectiveness of the main result. Consider a 2-DOF teleoperation system (1) with the following parameters:

$$\begin{aligned} M_i(q_i) &= \begin{bmatrix} M_{i11}(q_i) & M_{i12}(q_i) \\ M_{i21}(q_i) & M_{i22}(q_i) \end{bmatrix}, \\ C_i(q_i, \dot{q}_i) &= \begin{bmatrix} C_{i11}(q_i, \dot{q}_i) & C_{i12}(q_i, \dot{q}_i) \\ C_{i21}(q_i, \dot{q}_i) & C_{i22}(q_i, \dot{q}_i) \end{bmatrix}, \\ G_i(q_i) &= \begin{bmatrix} G_{i1} \\ G_{i2} \end{bmatrix}, \end{aligned}$$

$$\begin{aligned} F_m &= J_m^T f_h, \\ F_s &= J_s^T f_e, \end{aligned} \quad (30)$$

for $i = m, s$, respectively, and

$$\begin{aligned} M_{i_{11}}(q_i) &= l_{i_2}^2 m_{i_2} + l_{i_1}^2 (m_{i_1} + m_{i_2}) + 2l_{i_1} l_{i_2} m_{i_2} \cos(q_{i_2}), \\ M_{i_{22}}(q_i) &= l_{i_2}^2 m_{i_2}, \\ M_{i_{12}}(q_i) &= M_{i_{21}}(q_i) = l_{i_2}^2 m_{i_2} + l_{i_1} l_{i_2} m_{i_2} \cos(q_{i_2}), \\ C_{i_{11}}(q_i, \dot{q}_i) &= -l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) \dot{q}_{i_2}, \\ C_{i_{12}}(q_i, \dot{q}_i) &= -l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) (\dot{q}_{i_1} + \dot{q}_{i_2}), \\ C_{i_{21}}(q_i, \dot{q}_i) &= l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) \dot{q}_{i_1}, \\ C_{i_{22}}(q_i, \dot{q}_i) &= 0, \\ G_{i_1}(q_i) &= \frac{1}{l_{i_2}} g l_{i_2}^2 m_{i_2} \cos(q_{i_1} + q_{i_2}) \\ &\quad + \frac{1}{l_{i_1}} (l_{i_2}^2 m_{i_2} + l_{i_1}^2 (m_{i_1} + m_{i_2}) - l_{i_2}^2 m_{i_2}) \cos(q_{i_1}), \\ G_{i_2}(q_i) &= \frac{1}{l_{i_2}} g l_{i_2}^2 m_{i_2} \cos(q_{i_1} + q_{i_2}). \end{aligned} \quad (31)$$

The masses of the manipulators are chosen as $m_{m_1} = 1.5$ kg, $m_{m_2} = 0.75$ kg, $m_{s_1} = 2.5$ kg, and $m_{s_2} = 1.5$ kg, and the lengths of links for the master and the slave robots are $l_{m_1} = l_{s_1} = 0.5$ m and $l_{m_2} = l_{s_2} = 0.3$ m. The Jacobians of the master and slave robots are given by $J_i(q_i) = \begin{bmatrix} -l_{i_1} \sin(q_{i_1}) - l_{i_2} \sin(q_{i_1} + q_{i_2}) & -l_{i_2} \sin(q_{i_1} + q_{i_2}) \\ l_{i_1} \cos(q_{i_1}) + l_{i_2} \cos(q_{i_1} + q_{i_2}) & l_{i_2} \cos(q_{i_1} + q_{i_2}) \end{bmatrix}$.

The following parameterization is proposed for both manipulators with $i = m, s$, respectively:

$$\begin{aligned} Y_i(q_i, \dot{q}_i, \ddot{q}_i) &= \begin{bmatrix} \ddot{q}_{i_1} & Y_{12} & \ddot{q}_{i_2} & g \cos(q_{i_1} + q_{i_2}) & g \cos(q_{i_1}) \\ 0 & Y_{22} & \ddot{q}_{i_1} + \ddot{q}_{i_2} & g \cos(q_{i_1} + q_{i_2}) & 0 \end{bmatrix}, \\ Y_{12} &= 2 \cos(q_{i_2}) \ddot{q}_{i_1} + \cos(q_{i_2}) \ddot{q}_{i_2} - 2 \sin(q_{i_2}) \dot{q}_{i_1} \dot{q}_{i_2} \\ &\quad - \sin(q_{i_2}) \dot{q}_{i_2}^2, \\ Y_{22} &= \cos(q_{i_2}) \ddot{q}_{i_1} + \sin(q_{i_2}) \dot{q}_{i_1}^2, \\ \theta_i &= \text{col} \{ \theta_{i_1}, \theta_{i_2}, \theta_{i_3}, \theta_{i_4}, \theta_{i_5} \}, \end{aligned} \quad (32)$$

where $\theta_{i_1} = l_{i_2}^2 m_{i_2} + l_{i_1}^2 (m_{i_1} + m_{i_2})$, $\theta_{i_2} = l_{i_2}^2 m_{i_2} + l_{i_1}^2 (m_{i_1} + m_{i_2})$, $\theta_{i_3} = l_{i_2}^2 m_{i_2}$, $\theta_{i_4} = l_{i_2} m_{i_2}$, and $\theta_{i_5} = l_{i_1} (m_{i_1} + m_{i_2})$. We assume

FIGURE 1: The rectangle human input force.

FIGURE 2: The master and slave robots position: link 1.

FIGURE 3: The master and slave robots position: link 2.

that the operator hand force at the Y-direction is generated by a step signal depicted in Figure 1, while at the X-direction, there is no external force; then, we have $F_h = [0, 1]^T F_{h_y}$. The slave is in free motion in this simulation. By applying the designed controller (6), (8), (9), (10), and (11) with $K_m = K_s = 5I$, $\lambda_m = \lambda_s = 0.5$, we obtain the simulation results as shown in Figures 2 and 3. It can be seen that, under the proposed controller, the presence of parametric uncertainties

FIGURE 4: The dynamic parameter θ_m and the parameter estimate $\hat{\theta}_m$.

FIGURE 5: The dynamic parameter θ_s and the parameter estimate $\hat{\theta}_s$.

does not violate the stability of the bilateral teleoperation. The master and the slave achieve synchronization around the time $t = 10$ s. Furthermore, the estimated dynamic parameters are shown in Figures 4 and 5, respectively. By Figure 4, it is easy to find that the estimate $\hat{\theta}_m$ converges to its real value θ_m after $t = 2$ s, at which time the external human force starts to be exerted to the master manipulator. Similarly, Figure 5 reveals the convergence of the slave's dynamic parameters to their true values.

6. Conclusion

In this paper, a novel adaptive control framework that addressed dynamic uncertainties and time-varying delays for nonlinear teleoperation systems was proposed. Contrary to the existing works which guarantee the boundedness of the parameter estimation errors, this paper achieves convergence of parameters to their true values, which then gives rise to an improvement of system performance. By designing a new prediction error, the condition of PE is relaxed in this paper. The controller performance is verified via simulations. Further studies on parameter-converging adaptive control of teleoperation systems with a configuration of single master

and multiple slaves are underway and the results will be reported in the near future.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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