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Adaptive bilateral control for nonlinear uncertain teleoperation with guaranteed transient performance

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SUMMARY
Due to the special working environment of teleoperation, there are usually uncertainties existing in the dynamics of teleoperating robots. In this paper, an adaptive bilateral control scheme is proposed for the nonlinear teleoperation with parameterized dynamic uncertainties and time delays. Compared to the existing time-delay adaptive bilateral controllers, the proposed scheme has the advantage of faster and more accurate parameter adaptation. In this way, the transient performance of teleoperators can be improved without increasing the control gains, which is helpful for stability of teleoperation. The adaptive bilateral controller is designed to be applicable both in free motion and in constrained motion. The synchronization errors in the unconstrained subspace are asymptotically convergent under time delays. In the constrained subspace, the contact force remains bounded with the proposed controller. The stability of teleoperation is proved using Lyapunov methods and the passivity theory. Simulation results demonstrate the effectiveness of the proposed method.

KEYWORDS: Teleoperation; Bilateral control; Adaptive control; Transient performance; Time delays.

1. Introduction

During the past decades, teleoperation technologies have found a wide range of applications such as on-orbit service,[1] nuclear facilities maintenance,[2]telesurgery,[3]underwater exploration,[4] and so on. In bilateral teleoperation, the human operator at local site indirectly interacts with environments via the master-slave dual robotic mechanisms. At the same time, the contact information is fed back from the remote site to the local site, providing the operator with a more extensive sense of telepresence.

In bilateral teleoperation, the master and the slave robots are typically coupled via a communication network, which usually suffers from substantial time delays, data limitations and information losses. As it is well known, the existence of time delays would destroy the stability of teleoperation. Much effort has been devoted to overcome the time-delay instability. Most of the studies are based on the passivity formalism, such as scattering theory and the wave variable approach.[5–7] Both of them guarantee stability of the bilateral teleoperators by preserving the passivity of the communication channel. A series of subsequent researches were carried out based on these two approaches. For more advanced surveys, the reader may refer to Hokayem and Spong,[8] in which position feedback, impedance matching, robustness to time-varying delays, time-domain passivity approach, and various other objectives were introduced.

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To synchronize the positions of master and slave manipulators, a PD-based control scheme for teleoperation was proposed by Lee and Spong.[9] In their approach, the Lyapunov–Krasovskii technique and Parseval's identity were utilized to maintain the passivity of the closed-loop system. Nuno[10,11] designed a simple PD-like bilateral controller and the corresponding stability criterion was derived.

In real-world applications, the dynamic parameters of teleoperators are usually not exactly known. When the slave robots work in unstructured environments, the dynamics may change when contacts happen. Many adaptive control methods have been proposed for teleoperation with uncertainty,[12] among which some controllers are designed with communication delay compensating ability. Chopra[13] proposed an adaptive controller (AC) for the time-delay teleoperators without using scattering transformation. Nuno[14] pointed out the limitation of Chopra's scheme and proposed a more general AC for nonlinear teleoperators. However, their methods cannot ensure the accuracy of the estimates because the persistent excitation condition[15] is difficult to satisfy during teleoperation.

Most of the existing researches focus on the bilateral tracking errors in the steady state.[9–14] Few of them address the transient performance of the teleoperators. Therefore, the convergence time during synchronization cannot be guaranteed, especially with the existence of time delays and environment contacts. In the field of robot control, many successful schemes have been proposed to improve the transient performance.[16–18] A novel L1 AC with guaranteed transient performance was proposed by Cao and Hovakimyan.[19,20] However, these methods could not be directly applied on teleoperators. Firstly, there are time delays existing in bilateral control. Secondly, unlike the robot trajectory control, it is difficult to obtain the reference acceleration trajectory in teleoperation. The L1 adaptive control was originally proposed for linear system. Although L1 adaptive theory was extended to dealing with the time-varying nonlinear system,[21] it is still limited in practical use because of too many assumptions and preconditions.

In this paper, an adaptive bilateral controller is proposed for the uncertain nonlinear teleoperation with time delays. The Lyapunov–Krasovskii technique is adopted to maintain the stability of the closed-loop system. An adaptive law is used to compensate the synchronization errors. It has been pointed out that the loop gain should be limited for system stability.[22,23] Therefore, it is not recommended to choose too high control gains to enhance the transient performance. In this approach, the transient performance is guaranteed by means of a fast parameter estimation process. The adaptive bilateral control scheme is designed for both free motion case and constrained space teleoperation.

The remaining parts of this paper are organized as follows. The dynamics of mechanical teleoperators are given in Section 2. An AC is designed for the teleoperators in free motion firstly in Section 3.1. Based on the work of Section 3.1, a more general adaptive bilateral controller is proposed in Section 3.2. The performance and stability are also analyzed. In Section 4, simulation works are performed to verify the proposed method. The conclusion is drawn in Section 5.

2. Problem Formulation

Consider the teleoperation system composed by a couple of manipulators with n-DOF serial links and revolute joints. Taking account of the joint frictions, the dynamics of the teleoperators can be expressed as following Euler–Lagrange equations:[24]

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + D_m\dot{q}_m + g_m(q_m) = \tau_m + \tau_h \\ M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + D_s\dot{q}_s + g_s(q_s) = \tau_s + \tau_e. \end{aligned} \tag{1}$$

The subscript $i(i = m, s)$ denotes the master and the slave, respectively. $q_i \in \mathbb{R}^n$ are the vectors of generalized coordinates. $M_i(q_i) \in \mathbb{R}^{n\times n}$ are the corresponding inertia matrices; $C_i(q_i, \dot{q}_i) \in \mathbb{R}^{n\times n}$ are the Coriolis and centrifugal effects; $g_i(q_i) \in \mathbb{R}^n$ are the gravitational forces; $D_i \in \mathbb{R}^{n\times n}$ are positive-semidefinite diagonal matrices, denoting the joint friction coefficients.$\tau_m, \tau_s \in \mathbb{R}^n$ are control torques, $\tau_h \in \mathbb{R}^n$ is the force of human operator imposed on the master device, and $\tau_e \in \mathbb{R}^n$ is the force imposed on the slave robot when contact happens. Some properties of the model are given as follows:[25]

P1. The inertia matrices are uniformly positive definite with lower and upper bound,

$$0 < \lambda_{\min}\{M_i(q_i)\}I \le M_i(q_i) \le \lambda_{\max}\{M_i(q_i)\}I < \infty. \tag{2}$$

P2. The Coriolis and centrifugal matrices $C_i(q_i, \dot{q}_i)$ satisfy that $\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)$ are skew-symmetric, i.e.

$$\dot{M}_i(q_i) = C_i(q_i, \dot{q}_i) + C_i^T(q_i, \dot{q}_i). \tag{3}$$

P3. The models are linearly parameterizable with a proper definition of the robot parameters, which means, dynamics Eq. (1) can be rewritten as

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + D_i\dot{q}_i + g_i(q_i) = \tau_i = Y_i(q_i, \dot{q}_i, \ddot{q}_i)\theta_i, \tag{4}$$

where $Y_i(q_i, \dot{q}_i, \ddot{q}_i) \in \mathbb{R}^{n\times p}$ are matrices of known functions, and $\theta_i \in \mathbb{R}^p$ are constant vectors of the manipulators.

The master and slave are coupled by a network,

$$\begin{cases} q_s^d(t) = q_m(t - \Delta T), & \dot{q}_s^d(t) = \dot{q}_m(t - \Delta T) \\ q_m^d(t) = q_s(t - \Delta T), & \dot{q}_m^d(t) = \dot{q}_s(t - \Delta T) \end{cases}, \tag{5}$$

where ΔT is the time delay of the teleoperator system.

3. Adaptive Bilateral Controller Design

3.1. Teleoperation in free motion

Firstly, the case of free motion is studied. In this case, there is no external force imposed on both sides (the human operator force and the environment contact force are both zeroes). To simplify the analysis, the gravitational force is not considered. Then system Eq. (1) turns to be,

$$\begin{array}{l} M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + D_m\dot{q}_m = \tau_m \\ M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + D_s\dot{q}_s = \tau_s \end{array}. \tag{6}$$

In the free motion mode, two objectives should be achieved. The first one is to synchronize the configuration of the dual manipulators, with the synchronization errors defined as

$$\begin{array}{l} e_s(t) = q_s(t) - q_s^d(t) = q_s(t) - q_m(t - \Delta T) \\ e_m(t) = q_m(t) - q_m^d(t) = q_m(t) - q_s(t - \Delta T) \end{array}. \tag{7}$$

The second aim is to stabilize the dual manipulators, which means $\dot{q}_i \to 0$ as $t \to \infty$. Therefore, an auxiliary variable s_i is defined as

$$s_i = \dot{q}_i + \lambda e_i, \quad i = m, s, \tag{8}$$

where λ is a positive definite matrices representing the weight of synchronize errors.

Note that the acceleration signals are usually unavailable in teleoperation, so we define a new regressor about the synchronization errors, denoted as $\bar{Y}(\cdot)$:

$$M_i(q_i)\lambda\dot{e}_i + C_i(q_i, \dot{q}_i)\lambda e_i + D(\dot{q}_i)\lambda e_i = \bar{Y}_i(q_i, \dot{q}_i, e_i, \dot{e}_i)\theta_i \quad i = m, s. \tag{9}$$

From Eq. (9) it could be seen that when the synchronization errors are zeros, we have $\bar{Y}_i(q_i, \dot{q}_i, e_i, \dot{e}_i)\theta_i = 0$. The term $\bar{Y}_i(q_i, \dot{q}_i, e_i, \dot{e}_i)\hat{\theta}_i$ is a model-based term to compensate the errors, where $\hat{\theta}_i$ are the estimates of θ_i. Furthermore, a proportion term about s_i is added to compensate the synchronization errors. Besides, a local damper term is used to dissipate the extra energy introduced by time delays.[26] Finally, the bilateral control law is proposed as

$$\begin{cases} \tau_m = -\hat{M}_m(q_m)\lambda\dot{e}_m - \hat{C}_m(q_m, \dot{q}_m)\lambda e_m - \hat{D}_m(\dot{q}_m)\lambda e_m - k_m(\lambda e_m + \beta_m\dot{e}_m) - k_m\dot{q}_m \\ \tau_s = -\hat{M}_s(q_s)\lambda\dot{e}_s - \hat{C}_s(q_s, \dot{q}_s)\lambda e_s - \hat{D}_s(\dot{q}_s)\lambda e_s - k_s(\lambda e_s + \beta_s\dot{e}_s) - k_s\dot{q}_s \end{cases}, \tag{10}$$

where $\hat{M}_i$, $\hat{C}_i$ and $\hat{D}_i$ are estimates of the robot parameters, k_i are positive definite matrices denoting the proportion gains, and β_i are also positive definite matrices denoting the dissipation coefficient mentioned above.

Substituting the control law Eq. (10) into the teleoperation dynamics Eq. (6), and using the relationship Eq. (8), the closed-loop system is rewritten as,

$$M_i(q_i)\dot{s}_i + C_i(q_i, \dot{q}_i)s_i + D_i s_i = \bar{Y}_i(q_i, \dot{q}_i, e_i, \dot{e}_i)\tilde{\theta}_i - k_i(\lambda e_i + \beta_i \dot{e}_i) - k_i\dot{q}_i \quad i = m, s, \tag{11}$$

where $\tilde{\theta}_i$ is the estimation errors, given by $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$.

In the following part the adaptive law is derived. The notations $Y_i = Y_i(q_i, \dot{q}_i, \ddot{q}_i)$ and $\bar{Y}_i = \bar{Y}_i(q_i, \dot{q}_i, e_i, \dot{e}_i)$ will be used hereafter for simplicity, and the subscript i stands for $i = m, s$ unless otherwise specified. A straightforward choice of the adaptive law could be:

$$\dot{\hat{\theta}}_i(t) = \Gamma^{-1}(t)\bar{Y}_i^T \cdot s_i. \tag{12}$$

The adaptive law Eq. (12) was first proposed by J. Slotine[27] and has been widely used in adaptive control applications ever since. However, Slotine also pointed that adaptive law Eq. (12) cannot guarantee accurate estimations of parameters, unless the reference signals satisfy the so-called persistent excitation condition. In order to enhance the accuracy of estimation, some improvements should be made based on Eq. (12). In this work the computed torques are used to correct the adaption of estimations, and the prediction error of the estimated parameters is defined as

$$\varepsilon_i = \tau_i - Y_i\hat{\theta}_i = Y_i\tilde{\theta}_i. \tag{13}$$

The prediction error of computed torques could be used to correct the adaption estimations. Besides, another term about the estimation error is introduced to improve the convergence speed. The following adaptive law is proposed,

$$\begin{cases} \dot{\hat{\theta}}_i(t) = \Gamma^{-1}(t)\left(\bar{Y}_i^T \cdot s_i + (\xi_1 + \xi_2)z_i + \xi_1 Y_i^T \varepsilon_i\right) \\ \dot{z}_i(t) = -\eta z_i(t) + \mu Y_i^T \varepsilon_i - P_i(t)\dot{\hat{\theta}}_i(t) \end{cases}, \tag{14}$$

where $P_i(t)$ is the low-pass filtered signal of $Y_i^T Y_i$, i.e., $P_i(t) = \mu \int_0^t e^{-\eta(t-\sigma)} Y_i^T(\sigma)Y_i(\sigma)d\sigma$. μ and η are positive constants determining the property of low-pass filter. ξ_1 and ξ_2 are positive constants determining the convergence speed and error bounds (the relationship will be analyzed in the proof part). Define $Q_i(t) = Y_i^T Y_i$. Using the robust control techniques,[18] the coefficient ξ_1 is given by,

$$\xi_1 = \alpha \frac{\left\| \bar{Y}_i^T s \right\|}{\lambda_{\min}\left(Q_i(t)\right) + \delta}, \tag{15}$$

where α and δ are positive constants. The adaptive gain matrix $\Gamma(t)$ should satisfy that $\Gamma(t) > 0$, $\dot{\Gamma}(t) < 0$, so choose $\Gamma(t)$ as the following form,

$$\Gamma(t) = \mathrm{diag}\left\{\gamma_1(t), \ldots \gamma_p(t)\right\} \tag{16}$$

with $\gamma_i(t) = a_i e^{-\int_0^t f_i(\vartheta)d\vartheta} + b_i$, where a_i, b_i are positive constants, and $f_i(\vartheta)$ satisfies $f_i(\vartheta) \geq 0$.

Theorem 1.

(I) (Asymptotic tracking) In the case of free motion, the closed-loop teleoperators presented by Eq. (6) is stable under adaptive bilateral control law Eq. (10) and the adaptive law Eq. (14). More specifically, the joint velocities $\dot{q}_i$, the synchronization errors e_i, and the estimation errors $\tilde{\theta}_i$ satisfy that s_i, e_i, $\tilde{\theta}_i \in \mathcal{L}_\infty$ and

$$\dot{q}_i, e_i \to 0 \text{ as } t \to \infty, \quad i = m, s. \tag{17}$$

(II) (Transient performance) In the case of free motion, if the following inequality is satisfied for any $t > t_0$,

$$\mu \int_0^t e^{-\eta(t-\sigma)} Y_i^T(\sigma) Y_i(\sigma) d\sigma \geq \delta I, \tag{18}$$

then the states of teleoperators $x_i = [\dot{q}_i^T \; e_i^T \; \tilde{\theta}_i^T]^T$ converge to zeroes exponentially. Moreover, the estimation errors converge into a specified domain within a given time.

Proof. (I) Define a Lyapunov–Krasovskii candidate function $V(t)$ for the teleoperator system,

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t), \tag{19}$$

where

$$\begin{aligned} V_1(t) &= \frac{1}{2} \sum_{i=m,s} s_i^T M_i(t) s_i \qquad & V_2(t) &= \frac{1}{2} \sum_{i=m,s} \tilde{\theta}_i^T \Gamma(t) \tilde{\theta}_i \\ V_3(t) &= \frac{1}{2} \sum_{i=m,s} e_i^T \lambda^T k \beta e_i \qquad & V_4(t) &= \frac{1}{2} \sum_{i=m,s} \int_{t-\Delta T}^{t} \dot{q}_i^T(\sigma) k \beta \dot{q}_i(\sigma) d\sigma. \end{aligned} \tag{20}$$

Notice that $V(t)$ is radially unbounded in s_i, $\tilde{\theta}_i$, e_i and $\dot{q}_i$.
From property P2, one gets the following equation

$$\frac{1}{2} s_i^T \dot{M}(q) s_i = s_i^T C(q_i, \dot{q}_i) s_i. \tag{21}$$

Note that $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$, thus we have $\dot{\tilde{\theta}}_i = -\dot{\hat{\theta}}_i$. Using Eqs. (11), (14), and (21), the time derivative of Lyapunov–Krasovskii candidate Eq. (19) can be calculated,

$$\begin{aligned} \dot{V}(t) &= \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t) + \dot{V}_4(t) \\ &= -\sum_{i=m,s} \left[s_i^T (D_i + k_i) s_i + \frac{1}{2} \dot{e}_i^T k_i \beta_i \dot{e}_i + \tilde{\theta}_i^T \left((\xi_1 + \xi_2) P_i + \xi_1 Q_i \right) \tilde{\theta}_i - \frac{1}{2} \tilde{\theta}_i^T \dot{\Gamma} \tilde{\theta}_i \right]. \end{aligned} \tag{22}$$

From (16) it is shown that $\dot{\Gamma}$ is negative semidefinite, which gives the following inequality,

$$\dot{V}(t) \leq -\sum_{i=m,s} \left[s_i^T (D_i + k_i) s_i + \frac{1}{2} \dot{e}_i^T k_i \beta_i \dot{e}_i + \tilde{\theta}_i^T \left((\xi_1 + \xi_2) P_i + \xi_1 Q_i \right) \tilde{\theta}_i \right]. \tag{23}$$

The matrices $D_i + k_i$ and $k_i \beta_i$ are positive, and $(\xi_1 + \xi_2) P_i + \xi_1 Q_i$ are positive semidefinite, which means $\dot{V}(t) \leq 0$. Since $V(t) \geq 0$, one gets $s_i,\ e_i,\ \tilde{\theta}_i \in \mathcal{L}_\infty$. Utilizing Barbalat's lemma,[15] $\dot{V}(t)$ tends to zero asymptotically, thus s_i and $\dot{e}_i$ satisfy that $s_i,\ \dot{e}_i \to 0$ as $t \to \infty$.

Define $r(t) \triangleq q_m(t) + q_s(t)$. Calculating the sum of s_i, yields,

$$\lim_{t \to \infty} \dot{r}(t) + \lambda [r(t) - r(t - \Delta T)] = 0. \tag{24}$$

Define the Laplace transform of $r(t)$ as $R(s)$, and Eq. (24) can be represented by Laplacian operator s,

$$\lim_{s \to 0} s \left[s R(s) - r(0) + \lambda \left(R(s) - e^{-s\Delta T} R(s) \right) \right] = 0. \tag{25}$$

From Eq. (25) one can infer that $R(s)$ satisfies $\lim_{s \to 0} s^2 R(s) = 0$, which means $\dot{q}_m(t) + \dot{q}_s(t) \to 0$ as $t \to \infty$.

Now define $\bar{r}(t) = q_s(t) - q_m(t)$. Taking Laplace transform on $s_s - s_m$, and following the same outline as preceding proof, it could be proved that $\dot{q}_s(t) - \dot{q}_m(t) \to 0$ as $t \to \infty$. Thus, $\dot{q}_m(t)$ and

$\dot{q}_s(t)$ tend to zeroes asymptotically as $t \to \infty$. Considering the fact that $s_i = \dot{q}_i(t) + \lambda e_i(t) \to 0$, the asymptotic convergence of position synchronization errors can be proved, i.e. $e_i(t) \to 0,\ i = m, s$ as $t \to \infty$.

(II) If condition (18) holds, the matrix $(\xi_1 + \xi_2)P_i + \xi_1 Q_i$ in Eq. (23) is positive definite. This means that $s_i,\ \dot{e}_i,\ \tilde{\theta}_i \to 0$ as $t \to \infty$. So $\dot{q}_i, e_i$ and parameter estimation errors $\tilde{\theta}_i$ tend to zeroes asymptotically.

To illustrate the transient performance of the teleoperators, we start from the convergence of estimation errors $\tilde{\theta}$. A Lyapunov candidate function about $\tilde{\theta}$ is selected as

$$V_\theta(t) = \frac{1}{2}\tilde{\theta}^T \Gamma(t)\tilde{\theta}, \tag{26}$$

whose time derivative is given by

$$\begin{aligned} \dot{V}_\theta(t) &= \tilde{\theta}_i^T \Gamma(t)\dot{\tilde{\theta}}_i + \frac{1}{2}\tilde{\theta}_i^T \dot{\Gamma}(t)\tilde{\theta}_i \\ &\le -\tilde{\theta}_i^T \bar{Y}_i^T s_i - \tilde{\theta}_i^T(\xi_1 + \xi_2)z_i - \tilde{\theta}_i^T \xi_1 Y_i^T \varepsilon_i \\ &\le -\tilde{\theta}_i^T \bar{Y}_i^T s_i - \tilde{\theta}_i^T \left(\alpha \frac{\|\bar{Y}_i^T s\|}{\lambda_{\min}(Q_i(t)) + \delta} + \xi_2\right) P_i\tilde{\theta} - \tilde{\theta}_i^T \alpha \frac{\|\bar{Y}_i^T s\|}{\lambda_{\min}(Q_i(t)) + \delta} Y_i^T \varepsilon_i. \end{aligned} \tag{27}$$

If Eq. (18) holds, use the inequality $\alpha\beta \le \|\alpha\|\,\|\beta\|$ so that we obtain

$$\dot{V}_\theta(t) \le (1 - \alpha\,\|\tilde{\theta}\|)\,\|\bar{Y}_i^T s_i\|\,\|\tilde{\theta}\| - \xi_2\delta\,\|\tilde{\theta}\|^2. \tag{28}$$

In the case $\|\tilde{\theta}\| \ge 1/\alpha$, we have $\dot{V}_\theta(t) \le -\xi_2\delta\|\tilde{\theta}\|^2$. Since $V_\theta(t)$ is upper and lower bounded by

$$\lambda_m^\theta\,\|\theta\|^2 \le V_\theta(t) \le \lambda_M^\theta\,\|\theta\|^2, \tag{29}$$

where $\lambda_m^\theta = \lambda_{\min}(\Gamma(t)) = \min\{\gamma_i(t)\}$, and $\lambda_M^\theta = \lambda_{\max}(\Gamma(t)) = \max\{\gamma_i(t)\}$. Thus in this case $V_\theta(t)$ satisfies

$$V_\theta(t) \le -V_\theta(t_0)e^{-\xi_2\delta(t-t_0)/\lambda_M^\theta}. \tag{30}$$

We have

$$\|\tilde{\theta}(t)\| \le \sqrt{\frac{\lambda_M^\theta}{\lambda_m^\theta}}\,\|\tilde{\theta}(t_0)\|\,e^{-\frac{1}{2\lambda_M^\theta}\xi_2\delta(t-t_0)}, \tag{31}$$

so the parameter errors $\tilde{\theta}(t)$ will converge to a sphere $\Xi_\theta = \{\tilde{\theta} : \|\tilde{\theta}\| \le \frac{1}{\alpha}\cdot\sqrt{\lambda_M^\theta/\lambda_m^\theta}\}$ within a given time T_d from time t_0 with initial errors $\tilde{\theta}(t_0)$. The upper bound of T_d can be calculated from Eq. (31),

$$T_d = \begin{cases} 0, & \|\tilde{\theta}(t_0)\| < 1/\alpha \\ \dfrac{2\lambda_M^\theta}{\xi_2\delta}\ln\left(\alpha\tilde{\theta}(t_0)\right), & \|\tilde{\theta}(t_0)\| \ge 1/\alpha \end{cases}. \tag{32}$$

Since the convergence rate of parameter estimates is derived, the transient performance of the bilateral controller can be guaranteed. In fact, if we take the states of the teleoperation as $x_i = [\,\dot{q}_i^T\ e_i^T\ \tilde{\theta}_i^T\,]^T$, and choose the Lyapunov function

$$V_x(t) = \sum_{i=m,s} \frac{1}{2}x_i^T H_i x_i, \tag{33}$$

where H_i is a block diagonal matrix defined by

$$H_i = diag\left\{ M_i(t)\ \lambda^T M_i(t)\lambda + \lambda^{\mathrm{T}} k\beta\ \Gamma(t) \right\}. \tag{34}$$

The time derivative of $V_x(t)$ is

$$\dot{V}_x(t) = \sum_{i=m,s} \left\{ -s_i(D_i + k)s_i - \dot{q}_i^T k\beta\dot{e}_i - \tilde{\theta}_i^T\left((\xi_1 + \xi_2)P_i + \xi_1 Q_i\right)\tilde{\theta}_i + \frac{1}{2}\tilde{\theta}_i^T \dot{\Gamma}\tilde{\theta}_i \right\}. \tag{35}$$

In the case when master and slave are both in free motion, it is reasonable to make an assumption that $\dot{q}_i^d$ is zero. Note that the conclusion of Theorem 1(I) also supports that assumption. This implies,

$$\dot{V}_x(t) \leq -\gamma\ \|x\|^2 \tag{36}$$

with the definition of γ as follows,

$$\gamma = \min\left\{\lambda_{\min}\left(D_i + k(\mathrm{I} + \beta)\right),\ \lambda_{\min}\left(\lambda^T(D_i + k(\mathrm{I} + \beta))\lambda\right),\ \xi_2\delta\right\}. \tag{37}$$

Define the minimum and maximum eigenvalues of H_i as λ_m^H, λ_M^H. From Eq. (36) and the fact $\lambda_m^H\ \|x\|^2 \leq V_x(t) \leq \lambda_M^H\ \|x\|^2$, one can finally conclude that the states $x_i = [\,\dot{q}_i^T\ e_i^T\ \tilde{\theta}_i^T\,]^T$ converge to zeroes exponentially. More exactly,

$$\|x_i(t)\|^2 \leq \frac{\lambda_M^H}{\lambda_m^H}\ \|x_i(t_0)\|^2\, e^{-\frac{\mu}{\lambda_M^H}(t-t_0)}. \tag{38}$$

This completes the proof of Theorem 1.

Remark 1. The condition (18) is so-called the sufficient excitation (SE).[18] Compared to the persistent excitation (PE),[15] SE is weaker and thus is more suitable in teleoperation. Because the commands in teleoperation are made by the human operator and the reference trajectories are with more arbitrariness, PE is difficult to satisfy during the task. Therefore, it will be easier for the proposed approach to achieve accurate estimation than the other existing adaptive methods.

Remark 2. The transient performance of bilateral teleoperators is improved by the fast identification of robot parameters, rather than by increasing the gains of controller. Earlier researches have already pointed out that in time-delay teleoperation, high gains are not recommended for the sake of system stability.[22]

Remark 3. In the adaptive law Eq. (14), the calculation of prediction errors ε_i needs the regressor Y_i, which requires the information of joint acceleration. To avoid this, one can replace τ_i with filtered torques $\hat{\tau}_i$, and Y_i with a filtered regressor $W_i(q,\ \dot{q})$. The filtered dynamics could be rewritten as $\hat{\tau}_i = W_i(q,\ \hat{q})\theta_i$. This would not influence the parameter adaption. More details of the transformation could be found in Slotine.[15]

3.2. Teleoperation in constrained environment

When the slave robot moves in the constrained environment, sometimes it is impossible and unnecessary to require that the slave synchronizes with the master all the time, especially when the slave robot is contacting with hard environments. In this situation, force control strategies are often applied to regulate the contact force. In bilateral teleoperation, the communication between the master and the slave is limited by bandwidth and hardware. For example, in space robot teleoperation, the transmission frequency between the ground station and the space robot is only up to 10 Hz. Such control frequency cannot support the precise force control. Therefore, a better choice is that the bilateral controller only controls the positions of the dual robots, while the contact force is controlled in the remote site under higher frequency. Or rather, the bilateral controller performs the position tracking and the coarse force adjustments (rather than precise force control).

Firstly some assumptions are made about the environments.

A1. The obstacles are with high stiffness, which means the contact deformation is negligible for arbitrary high pressure.

A2. The frictional force is orthogonal to the pressure, i.e.

$$F_e = F_f + F_p, \quad F_f^T \cdot F_p = 0, \tag{39}$$

where F_e is the contact force, F_f, F_p are frictional force and pressure, respectively.

In adaptive bilateral control, a necessary step is the estimation of dynamic parameters. However, when high stiff contact happens to the slave robot, the equivalent dynamics parameters will probably alter dramatically to irrational values. For example, the estimates of masses may grow to infinity as tracking errors increasing. In adaptive control law Eqs. (10) and (14), this will consequently lead to too large control torques and generate an excessively high pressure, which is not desired in teleoperation. The main aim of our bilateral control method is to ensure the position tracking of dual robots in position subspace, and meanwhile, the contact force imposed on the slave robot remains bounded and controllable for human operator.

Note that the contact force F_e could be measured by force sensors mounted at the end of the slave manipulator. Define τ_e as the equivalent joint torques mapped from F_e. With the Jacobian matrix $J_s(q_s)$, τ_e is given by $\tau_e = J_s^T(q_s)F_e$. Then the dynamics of teleoperators could be rewritten as

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + D_m\dot{q}_m &= \tau_m + \tau_h \\ M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + D_s\dot{q}_s &= \tau_s + \tau_e. \end{aligned} \tag{40}$$

Define the projection of s_s to joint motion subspace as

$$\bar{s}_s = \begin{cases} \text{proj}(s_s, \ |\tau_e|\,\dot{q}_s), & |\tau_e| \geq \rho \\ s_s, & |\tau_e| < \rho \end{cases}, \tag{41}$$

where ρ is a small positive constant, standing for the threshold of contact force, and $s_s^{\perp}$ is the orthocomplement of $\bar{s}_s$. $\bar{e}_s$ and $e_s^{\perp}$ are also defined in the same way.

In constrained environment, the error $s_s^{\perp}$ is actually related to the combined dynamics of slave robot and environments. Therefore, only the errors in motion subspace are used to update the parameter. The adaptive law is given by

$$\begin{cases} \dot{\hat{\theta}}_i(t) = \Gamma^{-1}(t)\left(\bar{Y}_i^T(q_i, \dot{q}_i, \bar{e}_i, \dot{\bar{e}}_i)\cdot \bar{s}_i + (\xi_1+\xi_2)z_i + \xi_1 Y_i^T\varepsilon_i\right) \\ \dot{z}_i(t) = -\eta z_i(t) + \mu Y_i^T\varepsilon_i - P_i(t)\dot{\hat{\theta}}_i(t) \end{cases}. \tag{42}$$

The control law is still chosen as Eq. (10), then we have the following conclusion for the constrained teleoperation.

Theorem 2. When the environment contact happens to the slave robot, the teleoperator system (40) with bilateral AC (10), (42) is stable. Synchronization errors in unconstrained subspace $\bar{e}_i$ and parameter estimation errors $\tilde{\theta}_i$ converge to zeroes asymptotically. Moreover, the contact force is bounded under the bilateral control law.

Proof. Since the tracking performance is considered only in the position subspace, the Lyapunov–Krasovskii functional candidate is selected as

$$\bar{V}(t) = \frac{1}{2}\sum_{i=m,s}\left[\bar{s}_i^T M_i(t)\bar{s}_i + \tilde{\theta}_i^T\Gamma(t)\tilde{\theta}_i + \bar{e}_i^T\lambda^T k\beta\bar{e}_i + \int_{t-\Delta T}^{t}\dot{q}_i^T(\sigma)k\beta\dot{q}_i(\sigma)d\sigma\right]. \tag{43}$$

Using the fact that $s = \bar{s} + s^{\perp}$, and $e = \bar{e} + e^{\perp}$, the time derivative of $\bar{V}(t)$ could be written as

$$\begin{aligned} \dot{\bar{V}}(t) = &\underbrace{-\bar{s}_s^T M_s(t)\dot{\bar{s}}_s - \bar{s}_s^T C_s(t)\bar{s}_s - \bar{s}_s^T D_s\bar{s}_s - \bar{s}_s^T k(\lambda\bar{e}_s + \beta\dot{\bar{e}}_s) - \bar{s}_s^T k\dot{q}_s}_{\Delta_1} \\ &- \bar{s}_s^T\left[M_s(t)\dot{s}_s^{\perp} + C_s(t)s_s^{\perp} + Ds_s^{\perp} + k(\lambda e_s^{\perp} + \beta\dot{e}_s^{\perp}) - \tau_e\right] - \tilde{\theta}_s^T\left[(\xi_1+\xi_2)z_s + \xi_1 Y_s^T\varepsilon_s\right] \end{aligned}$$

$$\underbrace{+\bar{s}_s^T M_s(t)\dot{\bar{s}}_s + \frac{1}{2}\bar{s}_s^T \dot{M}_s(t)\bar{s}_s + \bar{e}_i^T \lambda^T k\beta\dot{\bar{e}}_i + \frac{d}{dt}\int_{t-\Delta T}^{t} \dot{q}_s^T(\sigma)k\beta\dot{q}_s(\sigma)d\sigma}_{\Delta_2} + \bar{s}_s^T \bar{Y}$$
$$\times (q_s, \dot{q}_s, e_s^\perp, \dot{e}_s^\perp)\tilde{\theta}_s + \dot{\bar{V}}_m(t), \tag{44}$$

where $\dot{\bar{V}}_m(t)$ denotes the master robot parts and is the same as that in Eq. (22).

Note that under assumption A1, the following equation holds,

$$M_s(t)\ddot{q}_s^\perp + C(t)\dot{q}_s^\perp + D\dot{q}_s^\perp = 0. \tag{45}$$

Considering the control torque (10), it is not difficult to conclude that the contact force satisfies

$$\hat{M}_s(t)\lambda\dot{e}_s^\perp + \hat{C}_s(t)\lambda e_s^\perp + \hat{D}\lambda e_s^\perp + k(\lambda e_s^\perp + \beta\dot{e}_s^\perp) = \tau_e^\perp = \tau_p. \tag{46}$$

Therefore, Eq. (44) can be represented as

$$\begin{aligned}\dot{\bar{V}}(t) &= \Delta_1 - \bar{s}_s^T\left[\tilde{M}_s(t)\lambda\dot{e}_s^\perp + \tilde{C}_s(t)\lambda e_s^\perp + D\lambda e_s^\perp - \tau_f\right] - \tilde{\theta}_s^T\left[(\xi_1+\xi_2)z_s + \xi_1 Y_s^T\varepsilon_s\right]\\ &\quad + \Delta_2 + \bar{s}_s^T\bar{Y}(q_s, \dot{q}_s, e_s^\perp, \dot{e}_s^\perp)\tilde{\theta}_s + \dot{\bar{V}}_m(t)\\ &= \Delta_1 - \bar{s}_s^T\bar{Y}(q_s, \dot{q}_s, e_s^\perp, \dot{e}_s^\perp)\tilde{\theta}_s + \bar{s}_s^T\tau_f - \tilde{\theta}_s^T\left[(\xi_1+\xi_2)z_s + \xi_1 Y_s^T\varepsilon_s\right]\\ &\quad + \Delta_2 + \bar{s}_s^T\bar{Y}(q_s, \dot{q}_s, e_s^\perp, \dot{e}_s^\perp)\tilde{\theta}_s + \dot{\bar{V}}_m(t),\end{aligned} \tag{47}$$

where τ_f are the mapped torques of the frictional force, which means

$$\tau_f = -\alpha_f\dot{q}_s, \tag{48}$$

where α_f is a positive definite frictional coefficient matrix.

Combining Eqs. (47) and (48), an inequality similar to Eq. (23) could be obtained,

$$\dot{\bar{V}}(t) \le -\sum_{i=m,s}\left[\bar{s}_i^T(D_i + k_i)\bar{s}_i + \frac{1}{2}\dot{\bar{e}}_i^T k_i\beta_i\dot{\bar{e}}_i + \tilde{\theta}_i^T\left((\xi_1+\xi_2)P_i + \xi_1 Q_i\right)\tilde{\theta}_i\right]. \tag{49}$$

Following the same proof outline as Theorem 1, conclusions about the convergence of $\tilde{\theta}_i$ and $\bar{e}_i$ can be obtained.

Now let us analyze the property of the contact force. Since the frictional force mainly depends on relative velocities and the materials, here we mainly concern with the pressure force between the slave robot and environments.

As is mentioned before, the pressure force can be mapped to the torques,

$$J^T(t)F_p = \tau_p \tag{50}$$

with τ_p given in Eq. (46). According to the convergence of $\tilde{\theta}$ and $\bar{e}_s$, also considering the boundedness of robot dynamic parameters (P1 and P2), the boundedness of τ_p could be derived. So it can be concluded that the contact pressure force F_p is bounded. This completes the proof.

Remark 4. Definition (41) implies that if the teleoperators move in free space, the controller becomes as the same as that in Section 3.1, hence, the AC (14), (42) proposed in this section is a more general approach which is applicable for both cases.

Remark 5. Only the boundedness of F_p could be concluded, because the magnitude of pressure force eventually depends on the human operator. As is shown in Eq. (46), F_p is determined by $e_s^\perp$ and $\dot{e}_s^\perp$, which share the same change tendency with e_m and $\dot{e}_m$ in spite of time delays. On the other hand, the human operator feels the feedback force, then accordingly adjusts q_m and $\dot{q}_m$ to achieve a desired reflected force. In this way, the contact force at the slave site gets adjusted coarsely.

Table I. Parameters of robots.

	Notation	Value	Unit
Length link 1	l_1	1	m
Length link 2	l_e	2	m
Mass link 1	m_1	1	kg
Mass link 2	m_e	3	kg
Link (1) center of mass	l_{c1}	1/2	m
Link (2) center of mass	l_{ce}	1	m
Inertia link 1	I_1	1/12	kg$\times$m^2
Inertia link 2	I_e	2/5	kg$\times$m^2
Offset angle of m_e	δ_e	0	deg

Remark 6. As is mentioned before, this approach does not aim to provide the precise force control. Due to the human physical features, the interaction between the operator and the master cannot supply stable and precise force commands. Only coarse adjustments about the contact force are supported under this control scheme. In fact, to achieve a precise force control, one can always add a local force controller in the force subspace of the slave robot without influencing the proposed bilateral control. However, the force controller is beyond the scope of this paper.

4. Simulations

In order to show the effectiveness of the proposed approach, simulations are performed in this section. The teleoperator system contains a pair of two-link robots,[27] representing the master and the slave, respectively. The dynamics of both robots are given by Eq. (1). Since the gravitational forces can be completely compensated in control, the gravity terms are not considered in simulations. The other terms of dynamics can be written in detail, as

$$M(q) = \begin{bmatrix} \alpha + 2\varepsilon\cos q_2 + 2\eta\sin q_2 & \beta + \varepsilon\cos q_2 + \varepsilon\sin q_2 \\ \beta + \varepsilon\cos q_2 + \varepsilon\sin q_2 & \beta \end{bmatrix}$$
$$C(\dot q, q) = \begin{bmatrix} (-2\varepsilon\sin q_2 + 2\eta\cos q_2)\,\dot q_2 & (-\varepsilon\sin q_2 + \eta\cos q_2)\,\dot q_2 \\ (\varepsilon\sin q_2 - \eta\cos q_2)\,\dot q_1 & 0 \end{bmatrix}, \tag{51}$$

where $\alpha = I_1 + m_1 l_{c1}^2 + I_e + m_e l_{ce}^2 + m_e l_1^2$, $\beta = I_e + m_e l_{ce}^2$, $\varepsilon = m_e l_1 l_{ce}\cos\delta_e$, and $\eta = m_e l_1 l_{ce}\sin\delta_e$. The parameters are given in Table I.

When the dynamics are represented in linearly parameterized form Eq. (4), the unknown parameters θ can be defined as $\theta = [\,\alpha\ \beta\ \varepsilon\ \eta\,]^T$. In the simulations $\delta_e = 0$, so there are three parameters to be estimated for the manipulator, which are α, β, and ε.

The simulations are carried out in MATLAB 7.10/Simulink environment. The SimMechanics tool box is used. Two typical tasks are performed. One is the case of free motion and the other is in constrained environments.

In the first simulation, both the master and the slave are initially at rest in free space. To illustrate the synchronization performance of the bilateral controller, the two robots start at different poses, with $q_m(0) = [\,45^\circ\ 60^\circ\,]^T$ and $q_s(0) = [\,0^\circ\ 0^\circ\,]^T$. The forward and backward time delays in communication are both 0.5s, i.e. $\Delta T = 0.5$. Because the true values of parameters are not available, we randomly choose a set of initial estimates as $\hat\theta_0 = [\,\hat a_0\ \hat\beta_0\ \hat\varepsilon_0\,]^T = [\,4.1\ 1.9\ 1.7\,]^T$. The trajectories of the manipulators are shown in Figs. 1–2. The results show that the synchronization errors in position and velocity both asymptotically converge to zero as claimed by Theorem 1.

In order to demonstrate the superiority of the proposed method, comparative simulations about the same task are carried out, in which the methods in literatures[14,28] are adopted. The simulation results are shown in Figs. 3–5. In the figures, ACGT (adaptive bilateral controller with guaranteed transient performance) stands for the proposed method, AC (adaptive controller for nonlinear teleoperators) is the method in Nuño,[14] and CAC (composite adaptive controller) denotes the method in Kim.[28] Figure 3 shows the synchronization errors of ACGT and AC in time-delay teleoperation. Both of the

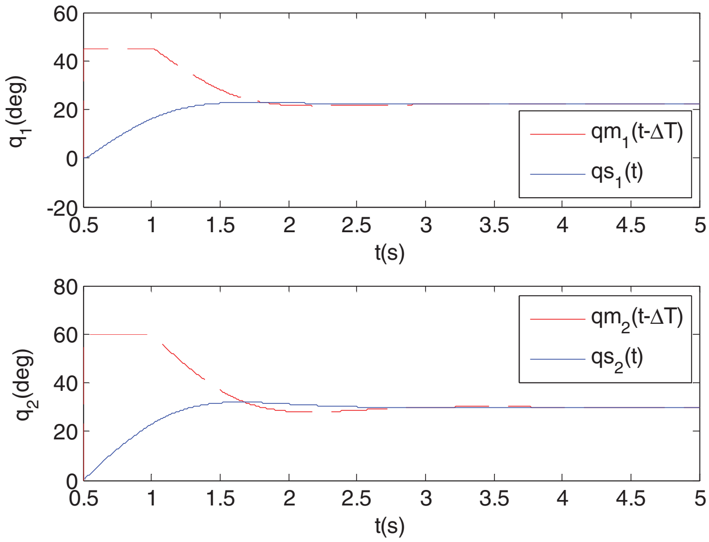


Fig. 1. Joint angles of the tele-manipulators.

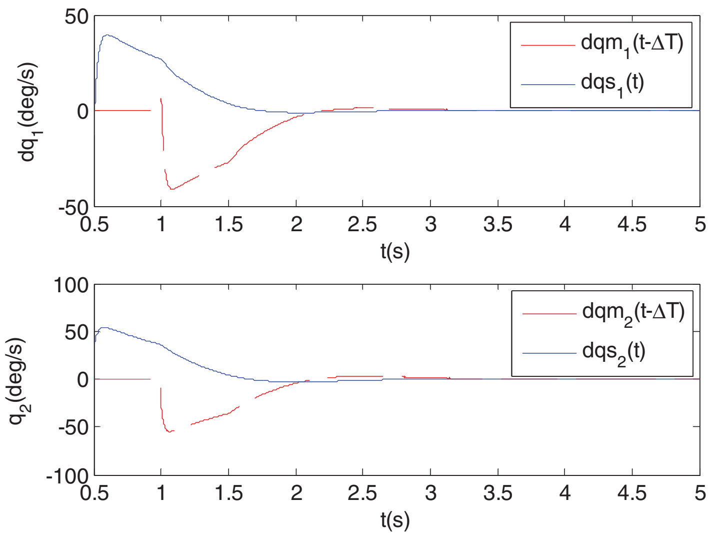


Fig. 2. Joint velocities of tele-manipulators.

two methods can achieve asymptotic tracking under time delays. It could be seen from Fig. 3(a) that the synchronization errors of ACGT are have been limited within no more than 2°since $t \approx 1.8$s, and the teleoperators turn into the steady state at time $t = 2.5$s. In Fig. 3(b), by contrast, the synchronization errors in joint angles are about 10°at time $t = 1.8$s, and the system endures a long slow creeping stage before it finally achieves the steady state at $t = 3$s. Therefore, the transient performance is improved with the use of ACGT. Figure 5 is the tracking errors of CAC. In teleoperation without time delays, transient performance is even better with CAC. However, CAC cannot guarantee stability in presence of time delays, as could be seen from Fig. 5(b). This could be explained by avoiding the use of local damping component in CAC. Local damping can enhance the robustness against time delays while at the same time degrades the response speed.

The estimates of the adaptive bilateral controller are displayed in Fig. 4. According to Table I, the true values of θ can be calculated: $\alpha = 6.733$, $\beta = 3.4$, and $\varepsilon = 3$. Figure 4(a) shows that the estimates converge to the true values within 2s under the proposed method. In contrast, stationary

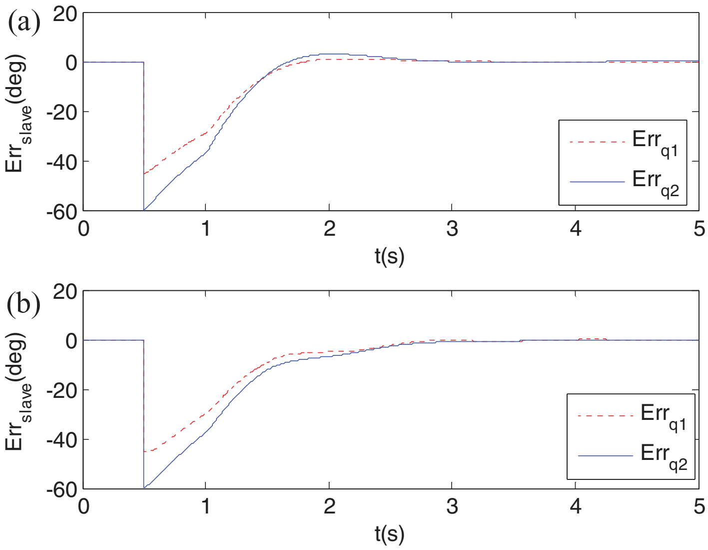


Fig. 3. Synchronization errors: (a) ACGT; (b) AC.

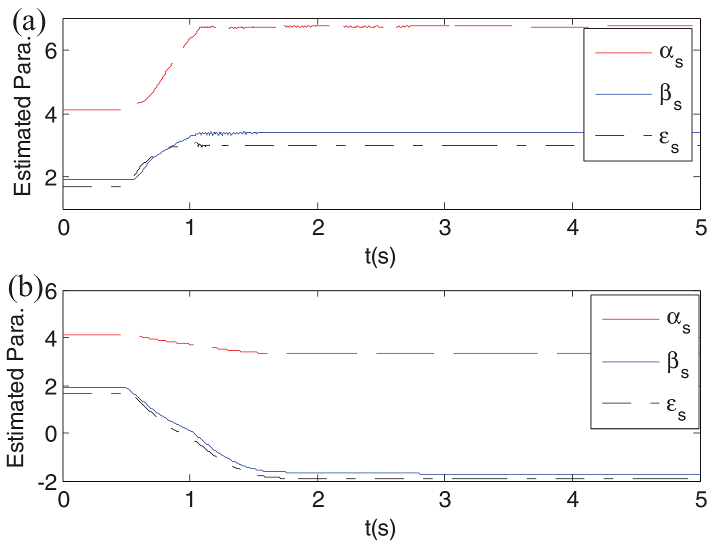


Fig. 4. Estimates: (a) ACGT; (b) AC.

errors exist in the estimates of AC as shown in Fig. 4(b). The reason for this has been stated in our previous analysis, in Remark 1.

The second simulation is performed in constrained environments. In the slave side, there is a wall along the line passing through two points $[-2, 2.232]$ and $[2, 2.232]$. The stiffness and damping coefficients of the wall obstacles are 10^4 N/m and 10^2Ns/m, respectively. The master and the slave are initially at the same pose. When the simulation starts, the human operator moves the master manipulator, and the slave robot follows the master. There is a period when the slave robot contacts with the wall. During this period, the slave will only track the master along the wall direction (position subspace). Firstly no time delay is added in communication. The initial estimates are set as the same as in the first simulation. The simulation results are shown in Figs. 6–9.

The teleoperators go through two modes during this simulation. From $t = 2$s to $t = 4$s, the slave contacts with the wall, moving in constrained environments, and in the rest time it moves in free space. The simulation results show that the slave could track the master well in the position subspace.

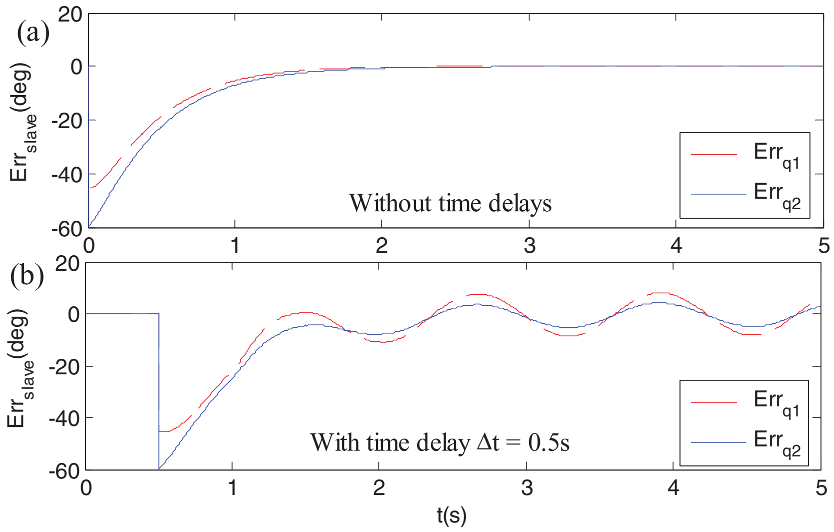


Fig. 5. Synchronization errors of CAC: (a) without time delays; (b) with time delays.

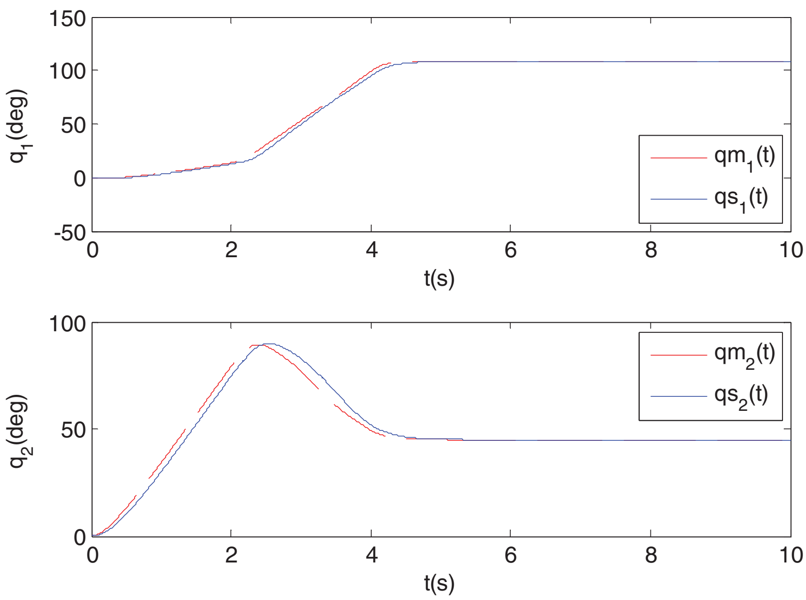


Fig. 6. Joint angles of slave.

When the contact happens, the slave can only track the master along the wall, so there are errors existing in joint angles and velocities. Figures 6 and 7 show that the errors during the contact period are not large. This is because that the features of human dynamics are considered in the simulation. When the tracking errors in contact direction become larger, the errors e_m in the master side also increase. Then the human operator will adjust the master accordingly to decrease the reflecting force. From Fig. 10 we could see that although contact happens, the estimates of the slave robot are still accurate. A comparative simulation with AC is also carried out in this task. Because the master moves slowly and the synchronization errors are small, the performance mainly differ in parameter estimation. Figure 11 shows that the estimates of AC once again converge to the untrue values.

The poses of the two robots during the simulation are shown in Fig. 12, where the left manipulator is the master and the right one is the slave.

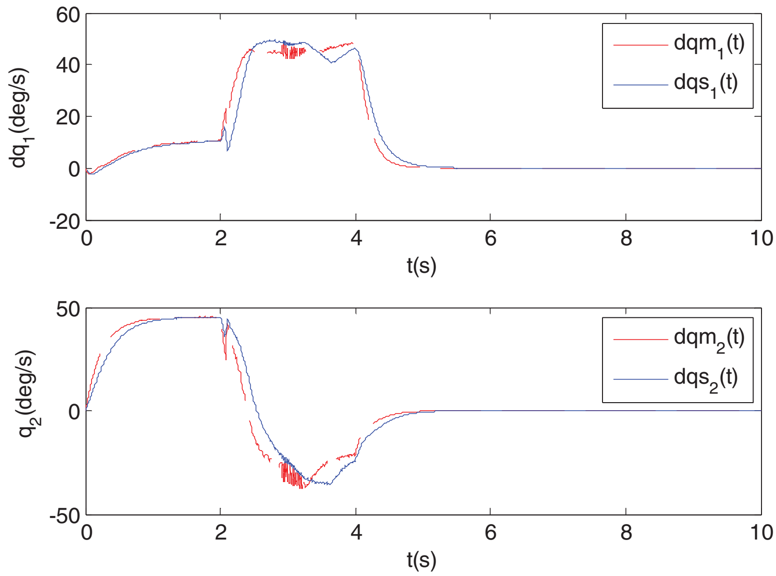


Fig. 7. Joint velocities of slave.

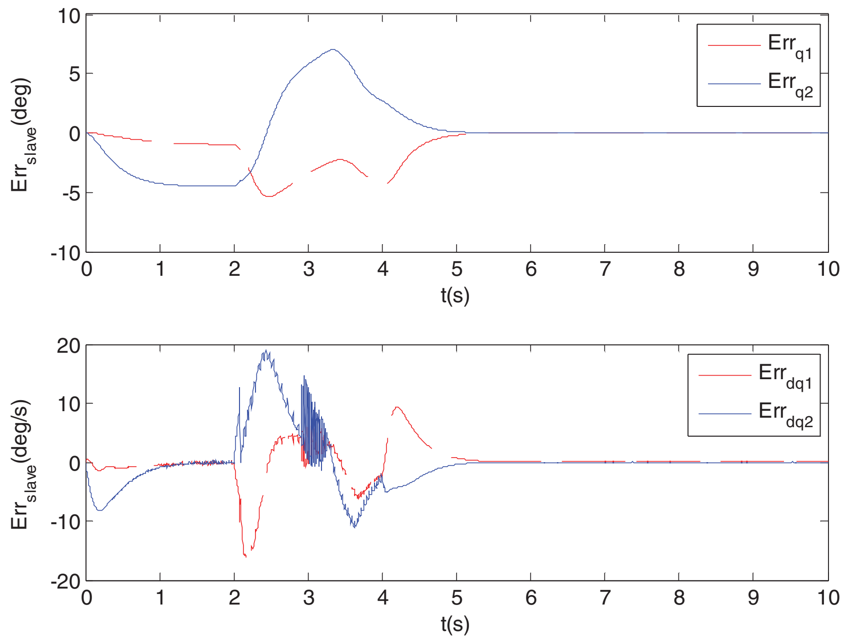


Fig. 8. Synchronization errors of slave.

When there are time delays existing in the constrained motion case, the tracking errors also converge to zero. Figure 13 shows the simulation results with $\Delta T = 0.5$. However, the existence of time delays may lead to too large contact forces, especially when the environment is with high stiffness (as is in Fig. 14). This is because the contact forces are reflected to the master with a lag and the human operator cannot adjust the master in time. As is mentioned earlier, this problem can be solved by adding a local force controller in the slave robot.

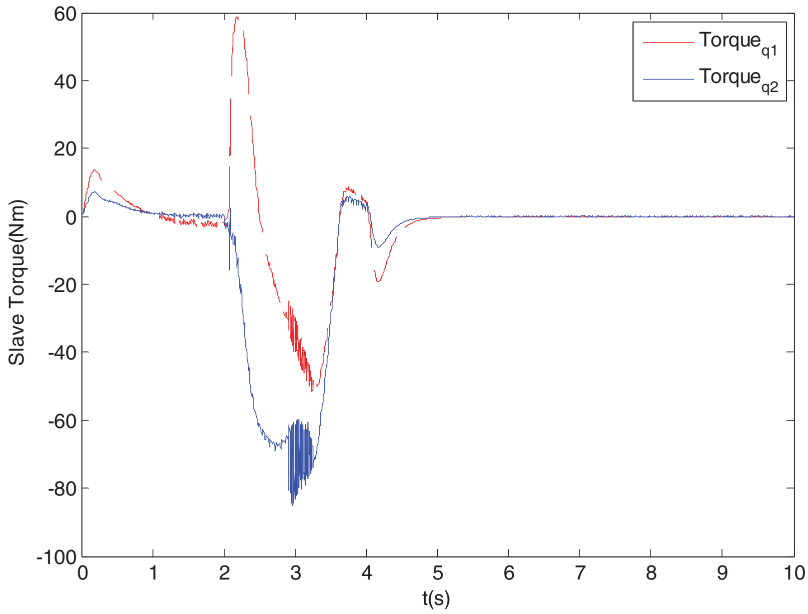


Fig. 9. Control torques of slave.

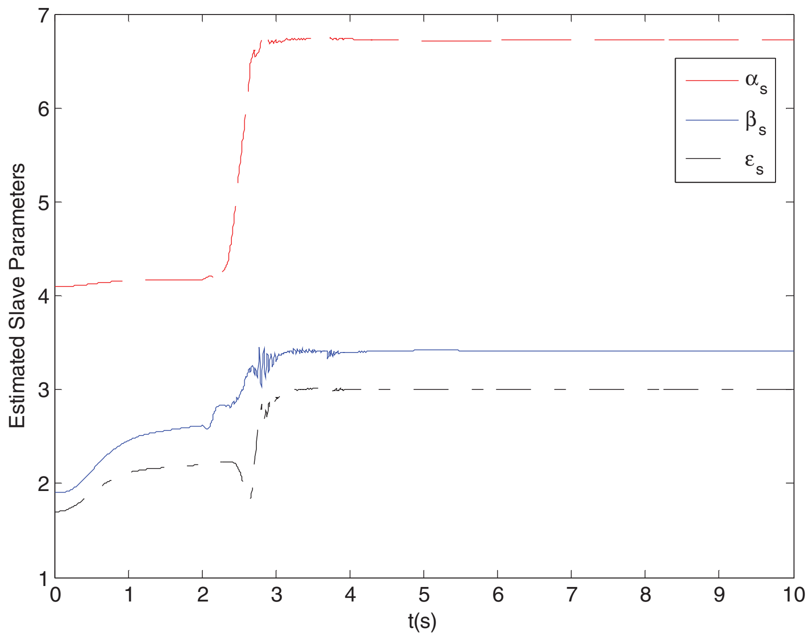


Fig. 10. Slave parameters estimates.

5. Conclusions

The problem of bilateral control for nonlinear time-delay teleoperation is studied in this paper. To compensate the synchronization errors of teleoperators with dynamic parameter uncertainties, an adaptive bilateral control method is proposed. In order to improve the transient performance of teleoperators, a faster and more accurate parameter estimating approach is utilized in the adaptive law. In this way, it does not need to increase the control gains to achieve the desired transient performance. This is helpful for system stability in the presence of time delays. By using Lyapunov methods and the passivity theory, the stability of the teleoperators is proved. The proposed bilateral adaptive control method can be applied in both free motion mode and constrained environments. In

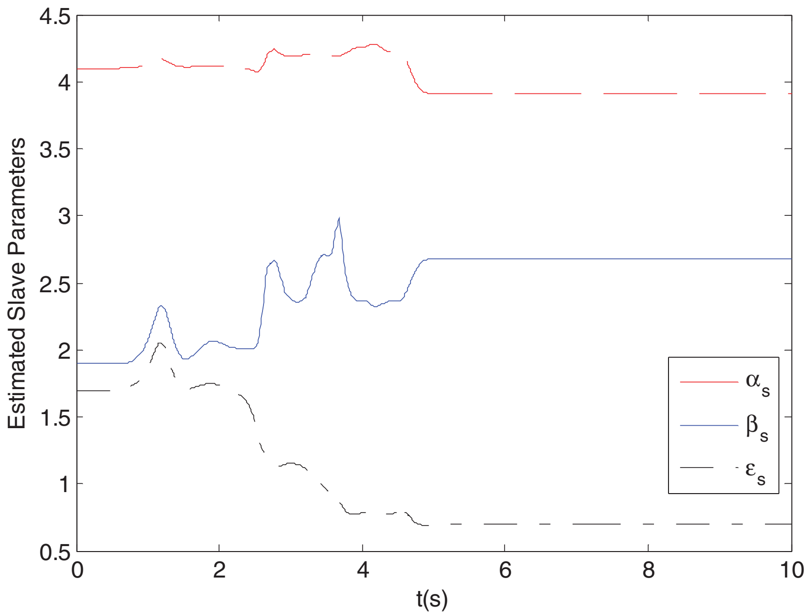


Fig. 11. Parameters estimates of AC.

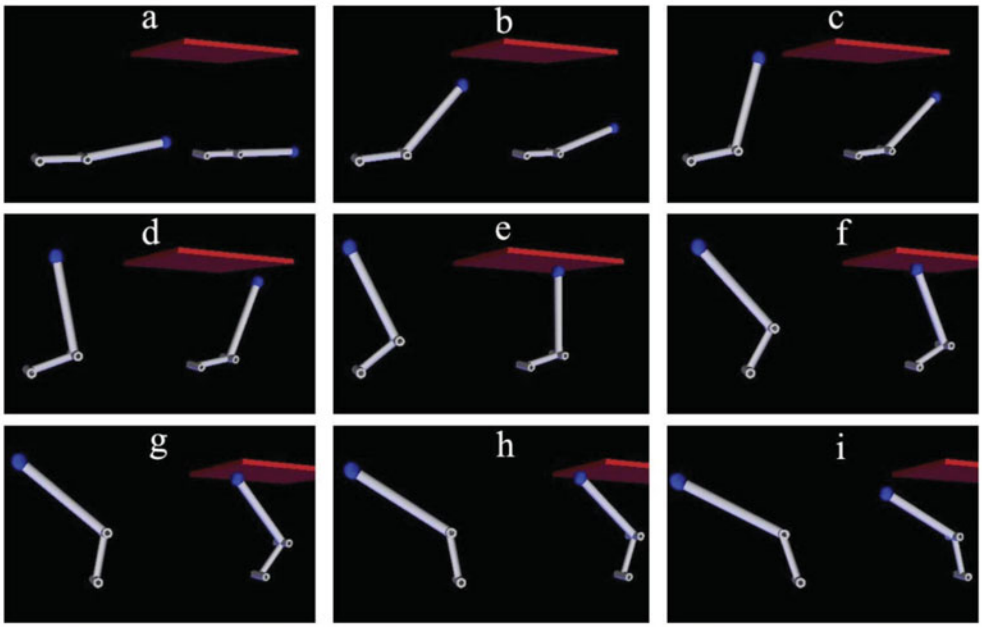
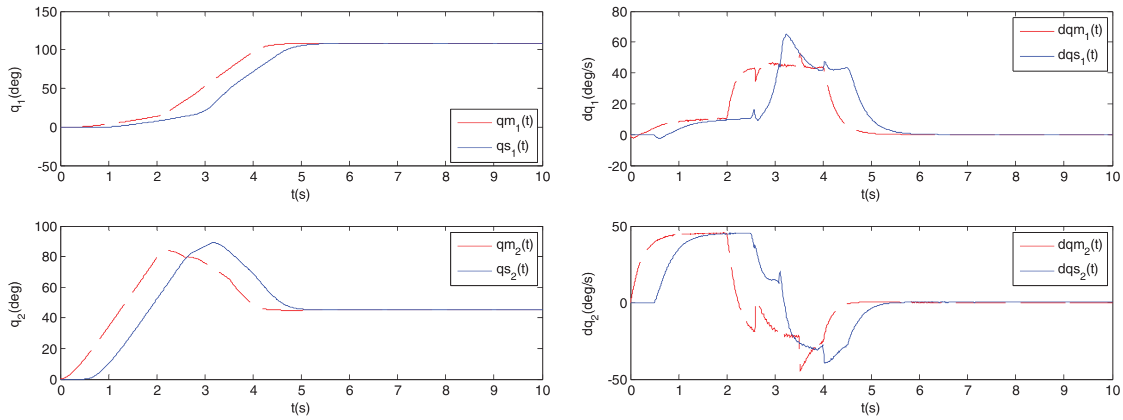


Fig. 12. Pose of the robots during the task.

free motion case, the synchronization errors of position and velocity asymptotically converge to zero. While in constrained environments, it is usually impossible to eliminate the tracking errors in the contact direction, so the tracking performance can only be guaranteed in unconstrained subspace. The contact forces are proved to be bounded, and can be roughly adjusted by the human operator. In the simulations, the proposed scheme is verified by a teleoperation system containing a pair of two-link manipulators. Comparisons with some recent adaptive control approaches indicate the advantage in transient performance and parameter estimation. The simulation results confirm the conclusions and demonstrate the effectiveness of proposed method.



(a) Joint angles of slave (b) Joint velocities of slave

Fig. 13. Tracking performance with time delay in constrained environments. (a) joint angles of slave; (b) joint velocities of slave.

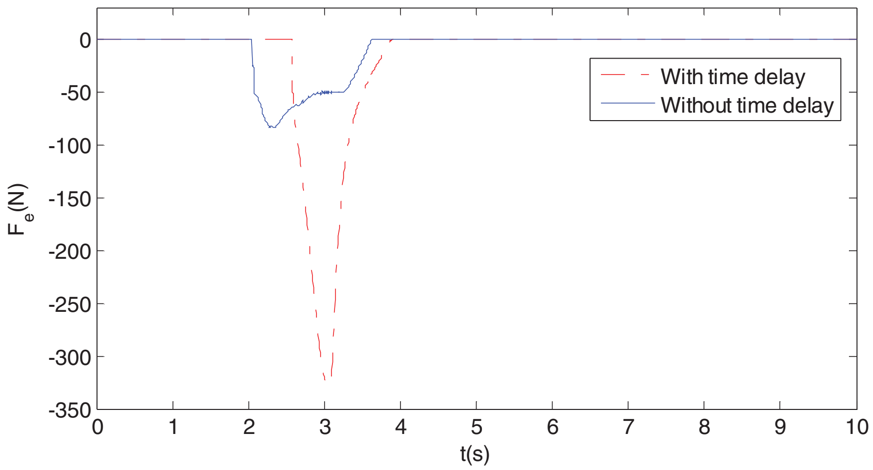


Fig. 14. Contact force in two cases.

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