J Intell Robot Syst
DOI 10.1007/s10846-012-9678-5

Adaptive Control for State Synchronization of Nonlinear Haptic Telerobotic Systems with Asymmetric Varying Time Delays

Farzad Hashemzadeh · Iraj Hassanzadeh · Mahdi Tavakoli · Ghasem Alizadeh

Received: 17 August 2011 / Accepted: 30 April 2012

Abstract In this paper, we introduce a new adaptive controller design scheme for nonlinear telerobotic systems with varying time delays where the delays and their variation rates are unknown. The designed controller has the ability to synchronize the state behaviors of the local and the remote robots. In this paper, asymptotic stability in the presence of varying time delays is of interest. Using the proposed controller, asymptotic stability of the bilateral telerobotic system subject to any bounded yet unknown varying delay with a bounded yet unknown rate of change can be guaranteed. Besides the varying time delay, the proposed adaptive controller has the ability to adapt to the parameter variations in the local and the remote robots' dynamics. It is shown that position and velocity errors between the local and the remote manipulators converge to the zero asymptotically, thus ensuring teleoperation transparency. Experimental and simulation results with a pair of PHANToM haptic devices and a pair of planar manipulators under varying time delays in the communication channel demonstrate the effectiveness of the proposed scheme.

Keywords Teleoperation · State synchronization · Varying time delay · Lyapunov–Krasovskii function · Adaptive control

F. Hashemzadeh (✉) · I. Hassanzadeh · G. Alizadeh
Department of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: farzad.hashemzadeh@ualberta.ca

I. Hassanzadeh
e-mail: ihassanz@ece.ualberta.ca

G. Alizadeh
e-mail: alizadeh@tabrizu.ac.ir

F. Hashemzadeh · I. Hassanzadeh · M. Tavakoli
Department of Electrical and Computer Engineering, University of Alberta,
Edmonton, AB, Canada
e-mail: mahdi.tavakoli@ualberta.ca

1 Introduction

Using a telerobotic system, a human operator can carry out tasks in a remote environment. Different applications of telerobotic systems vary from telesurgery to space manipulation. Teleoperation performance is greatly enhanced if haptic feedback about interaction occurring between the remote robot and the remote environment is provided to the human operator through the local robot [1]. Such systems are called *bilateral* as information flows in two directions between the operator and the remote environment [2]. On the other hand, in telerobotic applications with a distance between the local and the remote robots, there will be

Published online: 19 May 2012

a time delay in the communication channel of the system [3–5]; this time delay in the closed-loop system can destabilize the telerobotic system [5–7].

Control schemes have been developed to compensate for the time delay, most of which are based on the passivity theory. Passivity based control schemes [12–15] are inspired from energy interaction between interconnected systems [16]. Anderson and Spong [8] proposed scattering schemes based on the passivity theory. A similar passivity-based scheme is the wave variable formulation for two port networks proposed by Niemeyer and Slotine [9, 10]. These passivity based approaches can guarantee the passivity of bilateral teleoperation systems only for constant time delays [17].

In most passivity based bilateral teleoperation architectures, only velocity and force information is transmitted between the local and the remote sides [18]. This means that only force and velocity tracking can be ensured in such architectures, leaving the possibility that any initial position mismatch between the local and the remote robots would lead to a position drift between the robots. To solve this problem, one can transmit position information along with the velocity information through the communication channel [19–21].

The scattering and the wave variable approaches are the best known methods in the passivity based control framework, and have been the subject of recent studies concerning teleoperation under varying delays. An extension of the scattering approach to the case of varying time delays is reported in [11], in which a small positive gain is added in the communication channel to dissipate the extra energy generated due to the istorted scattered signals caused by varying time delay. The gain should be less than $1 - \dot{T}$, where T is the instantaneous value of the varying time delay, such that communication channel remains passive. Also, an extended version of the wave variable approach with varying time delay was reported in [22], in which besides the wave variables, extra variables are transmitted in the communication channel to preserve passivity.

Important schemes in passivity based control of manipulators in the presence of variable time delays include damping injection controllers usually referred to as P+d and PD+d [23]. The physical interpretation of damping injection controllers is that the interconnection between the remote and the local manipulators includes virtual dampers and springs. In damping injection controllers, a control gain affecting the velocity signals should have the exact value of $\sqrt{1 - \dot{T}}$. Although theses controllers guarantee asymptotic stability of velocities and position errors and are robust to time varying delays, their stability condition is not delay-independent and they are sensitive to rapid changes in delays. This is due to the variable gain $\sqrt{1 - \dot{T}}$, which depends on the time derivative of the delay [23].

Another interesting and recent topic in passivity-based analysis of telerobotic systems is the synchronization-based approach [24–26]. In synchronization-based schemes which its applications on bilateral teleoperation were studied in [24], all states including positions and velocities of local and the remote robots act synchronously.

In this paper, a new controller is proposed to guarantee asymptotic stability of the bilateral teleoperation system. The delay-independent proposed controller is an extension of the controller in [26] to the case of time varying delays and is able to synchronize the behavior of the local and the remote robots in the presence of unknown varying time delays in communication channel. In this paper, synchronization means asymptotic state (joint angle) tracking between the local and the remote robots. The proposed adaptive controller is able to guarantee state synchronization between the local and the remote robots in the presence of unknown varying time delays with unknown rates of variation. To use this controller, there is no need to know the robots parameters exactly; only estimations of the robots parameters are used in the controller. The controller parameters will change adaptively to guarantee the zero convergence of the tracking errors under robot parameter variations.

This paper is organized as follows. Section 2 concerns that tele-manipulator dynamic model while the controller design is presented in Section 3. In Sections 4 and 5, simulation and experimental results demonstrate the efficiency of the proposed controller followed by the conclusions presented in Section 6.

2 Tele-Manipulator Dynamic Model

The local and the remote manipulators can be modeled by the following nonlinear equations:

$$M_l(q_l)\ddot{q}_l + C_l(q_l,\dot{q}_l)\dot{q}_l + G_l(q_l) = \tau_h - \tau_l$$
$$M_r(q_r)\ddot{q}_r + C_r(q_r,\dot{q}_r)\dot{q}_r + G_r(q_r) = \tau_r - \tau_e \quad (1)$$

where q_i, $\dot{q}_i$ and $\ddot{q}_i$ for $i\epsilon\{r, l\}$ are the joint positions, velocities and accelerations of the local and the remote robots, respectively. Also, $M_i(q_i)$, $C_i(q_i,\dot{q}_i)$ and $G_i(q_i)$ are the inertia matrix, the Coriolis and centrifugal term and the gravitational force respectively, τ_l and τ_r are control torques for the local and the remote robots, andτ_h and τ_e are applied torques from the human operator and the environment sides respectively.

Some important properties of the above nonlinear dynamic model are [27, 28]:

1. For a manipulator with revolute joints, the inertia matrix $M_i(q_i)$ is symmetric positive definite and has the following upper and lower bounds:

   $$0 < \lambda_{\min}(M_i)\, I \le M_i(q_i) \le \lambda_{Max}(M_i)\, I \le \infty$$

   where I stands for identity matrix
2. For a manipulator, the relation between the Coriolis/centrifugal and the inertia matrices is as follows:

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

3. For a manipulator with revolute joints, there exists a positive number η bounding the Coriolis/centrifugal termas follows:

   $$|C_i(q_i,\dot{q}_i)\dot{q}_i| \le \eta \dot{q}_i^2$$

4. The nonlinear manipulator dynamics could be linearly parameterized as follows [28]:

   $$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = Y_i(q_i,\dot{q}_i,\ddot{q}_i)\,\theta_i$$

   where Y_i is a matrix of known functions of the generalized coordinates and their higher derivatives and θ_i is a vector of the manipulator dynamic parameters.

3 Control Design

In this part, the proposed controller to cope with varying time delays in a telerobotic system is presented. Since the model and consequently the dynamic equation of the system is uncertain. So, the estimates of the robots' dynamics are employed in the controllers τ_{l} and τ_{r}.

The controllers τ_l and τ_r in Eq. 1, are defined as follows

$$\tau_l = -\widehat{M}_l(q_l)\dot{e}_{pl} - \hat{C}_l(q_l,\dot{q}_l)e_{pl} - \hat{G}_l(q_l) + \overline{\tau}_l$$
$$\tau_r = \widehat{M}_r(q_r)\dot{e}_{pr} + \hat{C}_r(q_r,\dot{q}_r)e_{pr} + \hat{G}_l(q_l) - \overline{\tau}_r \quad (2)$$

where $\hat{}$ represents estimates of the remote and the local manipulators parameters and $\overline{\tau}_i$ for $i\epsilon\{l, r\}$ are the new control signals. Also, e_{pl} and e_{pr}, which are position errors in local and remote sides, are defined as

$$e_{pl} \triangleq q_r(t - T_2(t)) - q_l(t)$$
$$e_{pr} \triangleq q_l(t - T_1(t)) - q_r(t) \quad (3)$$

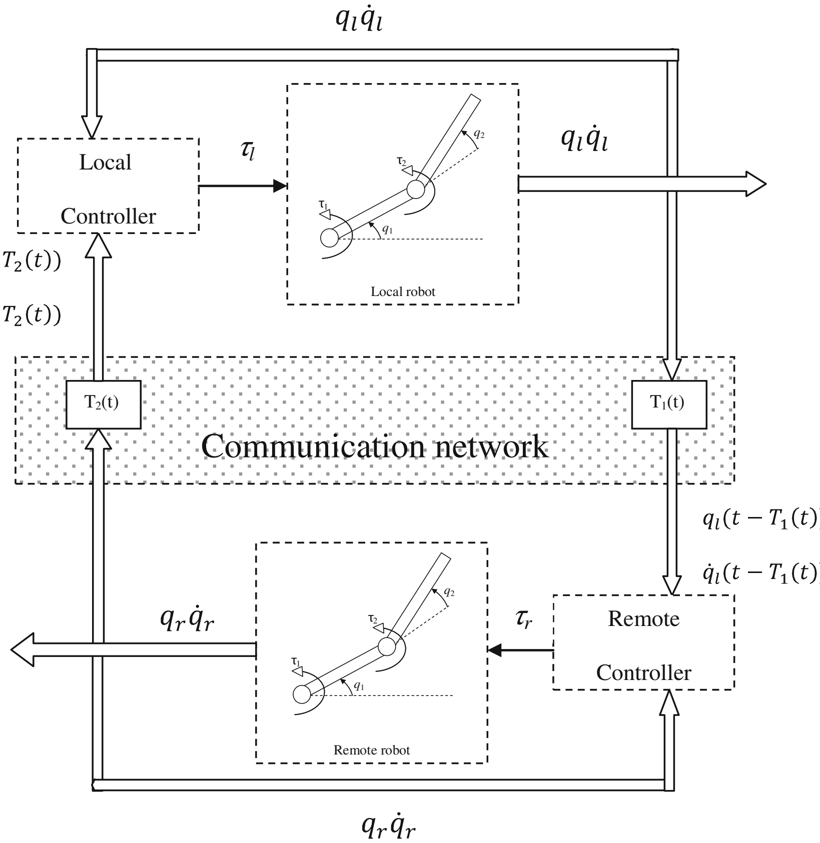
where $T_1(t)$ is the delay in the feedforward path and $T_2(t)$ is the delay in the feedback path. The overall scheme of teleoperation with varying time delay is shown in Fig. 1.

We proposed to define the new control signals, i.e., $\overline{\tau}_l$ and $\overline{\tau}_r$, as follows:

$$\overline{\tau}_l = \begin{cases} K_l\varepsilon_l - \frac{1}{2}\dot{e}_{pl} - \frac{1}{2}e_{vl} \\ \quad - \frac{e_{vl}^T(e_{pl} + \dot{e}_{pl} - e_{vl})}{2\|\varepsilon_l\|_2^2}\varepsilon_l, & \|\varepsilon_l\|_2 \ne 0 \\ 0, & \|\varepsilon_l\|_2 = 0 \end{cases}$$
$$\overline{\tau}_r = \begin{cases} K_r\varepsilon_r - \frac{1}{2}\dot{e}_{pr} - \frac{1}{2}e_{vr} \\ \quad - \frac{e_{vr}^T(e_{pr} + \dot{e}_{pr} - e_{vr})}{2\|\varepsilon_r\|_2^2}\varepsilon_r, & \|\varepsilon_r\|_2 \ne 0 \\ 0, & \|\varepsilon_r\|_2 = 0 \end{cases} \quad (4)$$

where K_i for $i\varepsilon\{l, r\}$ is a positive definite matrix and $\|.\|_2$ denotes Euclidean norm. Also, $\dot{e}_{pi}$ is the time derivative of position error e_{pi}, and e_{vi}

Fig. 1 The closed-loop teleoperation system under varying time delays



(velocity error) and ε_i for $i\varepsilon\{l, r\}$ are defined as follows:

$$\varepsilon_i \triangleq \dot{q}_i - e_{pi} \qquad i\epsilon\{l, r\}$$
$$e_{vl} \triangleq \dot{q}_r(t - T_2(t)) - \dot{q}_l$$
$$e_{vr} \triangleq \dot{q}_l(t - T_1(t)) - \dot{q}_r \tag{5}$$

Note that because of the variation of time delays, the velocity error e_{vi} and the derivative of the position error $\dot{e}_{pi}$ are not the same.

Combining Eqs. 2 and 1, the closed-loop system equations are found:

$$\begin{aligned} &M_l(q_l)\dot{\varepsilon}_l + C_l(q_l, \dot{q}_l)\varepsilon_l \\ &\quad = -\widetilde{M}_l(q_l)\dot{e}_{pl} - \widetilde{C}_l(q_l, \dot{q}_l)e_{pl} - \widetilde{G}_l(q_l) - \overline{\tau}_l + \tau_h \\ &M_r(q_r)\dot{\varepsilon}_r + C_r(q_r, \dot{q}_r)\varepsilon_r \\ &\quad = -\widetilde{M}_r(q_r)\dot{e}_{pr} - \widetilde{C}_r(q_r, \dot{q}_r)e_{pr} - \widetilde{G}_r(q_r) - \overline{\tau}_r - \tau_e \end{aligned} \tag{6}$$

where $\sim$ represents the estimation error in the manipulator parameters, e.g., $\widetilde{M}_i = M_i - \widehat{M}_i$, $\widetilde{C}_i = C_i - \widehat{C}_i$, and $\widetilde{G}_i = G_i - \widehat{G}_i$ for $i\epsilon\{l, r\}$.

Using the fact that the equations of robot motions are linear in their parameters (Property IV), let us define the regressor matrix Y_i and the parameter vector θ such that the nominal robot dynamics can be written as

$$M(q)\dot{e} + C(q, \dot{q})e + G(q) = -Y(q, \dot{q}, e, \dot{e})\theta \tag{7}$$

Equation 7 can be achieved from Property IV via replacing $\ddot{q}$ with $\dot{e}$ and the exterior $\dot{q}$ in $C(q, \dot{q})\dot{q}$ with e and then negating Y.

Using the above linearity property, we have

$$\begin{aligned} &Y_i\left(q_i, \dot{q}_i, e_{pi}, \dot{e}_{pi}\right)\widetilde{\theta}_i \\ &\quad = -\widetilde{M}_i(q_i)\dot{e}_{pi} - \widetilde{C}_i(q_i, \dot{q}_i)e_{pi} - \widetilde{G}_i(q_i), \quad i\epsilon\{l, r\} \end{aligned} \tag{8}$$

where $\widetilde{\theta}_i = \theta_i - \widehat{\theta}_i$ and the regressor $Y_i(q_i, \dot{q}_i, e_{pi}, \dot{e}_{pi})$ is a matrix whose elements are known functions of the generalized coordinates, derivatives of generalized coordinates, position errors and velocity errors. It is possible to find the following closed-loop dynamical equations from the above.

$$M_l(q_l)\dot{\varepsilon}_l + C_l(q_l, \dot{q}_l)\varepsilon_l = Y_l(q_l, \dot{q}_l, e_{pl}, \dot{e}_{pl})\widetilde{\theta}_l - \overline{\tau}_l + \tau_h$$
$$M_r(q_r)\dot{\varepsilon}_r + C_r(q_r, \dot{q}_r)\varepsilon_r = Y_r(q_r, \dot{q}_r, e_{pr}, \dot{q}_{pr})\widetilde{\theta}_r - \overline{\tau}_r - \tau_e \tag{9}$$

Now, we introduce the following adaptive update low for manipulators parameter estimation to be used in conjunction with the controllers (2):

$$\dot{\hat{\theta}}_i = \Gamma Y_i^T \varepsilon_i \, i\epsilon\{l, r\} \tag{10}$$

In the following, we analyze the stability of the system in the sense of Lyapunov.

Theory I In free motion ($\tau_h = \tau_e = 0$), the bilateral tele-manipulator (1) with the controller (2)–(5) is asymptotically stable in the sense of Lyapunov. Also, q_i converges to a constant value, and the position error e_{pi} and the velocity error e_{vi} converge to zero for any bounded varying time delay with a bounded time derivative. Here, $i\epsilon\{l, r\}$.

Proof To study the asymptotic stability in the sense of Lyapunov under varying time delays in the communication channel, we use the following Lyapunov–Krasovskii functional:

$$V = \frac{1}{2}\int_{t-T_1(t)}^{t} \dot{q}_l^T \dot{q}_l dt + \frac{1}{2}\int_{t-T_2(t)}^{t} \dot{q}_r^T \dot{q}_r dt + \frac{1}{2}\sum_{i\epsilon\{r,l\}}\left[\varepsilon_i^T M_i \varepsilon_i + \widetilde{\theta}_i^T \Gamma^{-1}\widetilde{\theta}_i + \frac{1}{2}e_{pi}^T e_{pi}\right] \tag{11}$$

where Γ is a positive definite matrix. The time derivative of V is

$$\begin{aligned}\dot{V} = &\sum_{i\epsilon\{r,l\}}\left[\frac{1}{2}\varepsilon_i^T \dot{M}\varepsilon_i + \varepsilon_i^T M\dot{\varepsilon}_i + \widetilde{\theta}_i^T\Gamma^{-1}\dot{\widetilde{\theta}}_i + \frac{1}{2}e_{pi}^T\dot{e}_{pi}\right] \\ &+ \frac{1}{2}\dot{q}_l(t)^T\dot{q}_l(t) - \frac{1}{2}\left(1-\dot{T}_1\right)\dot{q}_l(t-T_1(t))^T\dot{q}_l \\ &\times (t-T_1(t)) + \frac{1}{2}\dot{q}_r(t)^T\dot{q}_r(t) \\ &-\frac{1}{2}\left(1-\dot{T}_2\right)\dot{q}_r(t-T_2(t))^T\dot{q}_r(t-T_2(t))\end{aligned} \tag{12}$$

Using Eq. 9, we can simplify $\dot{V}$ as

$$\begin{aligned}\dot{V} = &\sum_{i\epsilon\{r,l\}}\left[\frac{1}{2}\varepsilon_i^T\dot{M}\varepsilon_i + \varepsilon_i^T\left\{-C_i\varepsilon_i + Y_i\widetilde{\theta}_i - \overline{\tau}_i\right\}\right. \\ &\left. + \widetilde{\theta}_i^T\Gamma^{-1}\dot{\widetilde{\theta}}_i + \frac{1}{2}e_{pi}^T\dot{e}_{pi}\right] + \frac{1}{2}\dot{q}_l(t)^T\dot{q}_l(t) \\ &- \frac{1}{2}\left(1-\dot{T}_1\right)\dot{q}_l(t-T_1(t))^T\dot{q}_l(t-T_1(t)) \\ &+ \frac{1}{2}\dot{q}_r(t)^T\dot{q}_r(t) - \frac{1}{2}\left(1-\dot{T}_2\right)\dot{q}_r(t-T_2(t))^T \\ &\times \dot{q}_r(t-T_2(t))\end{aligned} \tag{13}$$

Using the following skew-symmetry property, which is equivalent to the property II,

$$x^T\left(\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)\right)x = 0 \qquad \forall x \in R^n \tag{14}$$

and after some simplifications, we get:

$$\frac{1}{2}\varepsilon_i^T\dot{M}\varepsilon_i + \varepsilon_i^T\left\{-C_i\varepsilon_i + Y_i\widetilde{\theta}_i - \overline{\tau}_i\right\} + \widetilde{\theta}_i^T\Gamma^{-1}\dot{\widetilde{\theta}}_i = \widetilde{\theta}_i^T\left\{Y_i^T\varepsilon_i + \Gamma^{-1}\dot{\widetilde{\theta}}_i\right\} - \varepsilon_i^T\overline{\tau}_i \tag{15}$$

To simplify the right-hand side of Eq. 15, we introduce the following adaptive rule

$$\dot{\widetilde{\theta}}_i = -\Gamma Y_i^T\varepsilon_i \tag{16}$$

With the assumption that the variation of unknown parameters θ is slow, we get $\dot{\widetilde{\theta}} = -\dot{\hat{\theta}}$, and the above adaptive rule for parameter updates becomes

$$\dot{\widehat{\theta}}_i = \Gamma Y_i^T \varepsilon_i \tag{17}$$

which is same as Eq. 10.

Using the above, it is possible to simplify ă$\dot{V}$, as follows:

$$\begin{aligned}\dot{V} = &\sum_{i\epsilon\{r,l\}} \left[-\varepsilon_i^T \overline{\tau}_i + \frac{1}{2} e_{pi}^T \dot{e}_{pi}\right] + \frac{1}{2}\dot{q}_l(t)^T \dot{q}_l(t)\\ &- \frac{1}{2}\left(1-\dot{T}_1\right)\dot{q}_l(t-T_1(t))^T \dot{q}_l(t-T_1(t))\\ &+ \frac{1}{2}\dot{q}_r(t)^T \dot{q}_r(t) - \frac{1}{2}\left(1-\dot{T}_2\right)\\ &\times \dot{q}_r(t-T_2(t))^T \dot{q}_r(t-T_2(t))\end{aligned} \tag{18}$$

Using the definition of $\overline{\tau}_i$ in Eq. 4 and after some manipulations, we get

$$\begin{aligned}\dot{V} = &\sum_{i\epsilon\{r,l\}} \left[-\varepsilon_i^T K_i \varepsilon_i + \frac{1}{2}\varepsilon_i^T \dot{e}_{pi} + \frac{1}{2}\varepsilon_i^T e_{vi}\right.\\ &\left.\qquad + \frac{1}{2} e_{vi}^T\left(e_{pi} + \dot{e}_{pi} - e_{vi}\right) + \frac{1}{2} e_{pi}^T \dot{e}_{pi}\right]\\ &+ \frac{1}{2}\dot{q}_l(t)^T \dot{q}_l(t) - \frac{1}{2}\left(1-\dot{T}_1\right)\dot{q}_l(t-T_1(t))^T\\ &\times \dot{q}_l(t-T_1(t)) + \frac{1}{2}\dot{q}_r(t)^T \dot{q}_r(t)\\ &- \frac{1}{2}\left(1-\dot{T}_2\right)\dot{q}_r(t-T_2(t))^T \dot{q}_r(t-T_2(t))\end{aligned} \tag{19}$$

Applying the following relationships

$$\begin{aligned}&\frac{1}{2}\dot{q}_l(t)^T \dot{q}_l(t) - \frac{1}{2}\dot{q}_r(t-T_2(t))^T \dot{q}_r(t-T_2(t))\\ &\quad = -\frac{1}{2} e_{vl}^T e_{vl} - \dot{q}_l(t)^T e_{vl}\end{aligned} \tag{20}$$

$$\begin{aligned}&\frac{1}{2}\dot{q}_r(t)^T \dot{q}_r(t) - \frac{1}{2}\dot{q}_l(t-T_1(t))^T \dot{q}_l(t-T_1(t))\\ &\quad = -\frac{1}{2} e_{vr}^T e_{vr} - \dot{q}_r(t)^T e_{vr}\end{aligned} \tag{21}$$

it is found that

$$\begin{aligned}\dot{V} = &\sum_{i\epsilon\{r,l\}} \left[-\varepsilon_i^T K_i \varepsilon_i + \frac{1}{2}\varepsilon_i^T \dot{e}_{pi} + \frac{1}{2}\varepsilon_i^T e_{vi}\right.\\ &\left.\qquad + \frac{1}{2} e_{vi}^T\left(e_{pi} + \dot{e}_{pi} - e_{vi}\right) + \frac{1}{2} e_{pi}^T \dot{e}_{pi}\right]\\ &- \frac{1}{2} e_{vl}^T e_{vl} - \dot{q}_l(t)^T e_{vl}\\ &+ \frac{1}{2}\dot{T}_1 \dot{q}_l(t-T_1(t))^T \dot{q}_l(t-T_1(t))\\ &- \frac{1}{2} e_{vr}^T e_{vr} - \dot{q}_r(t)^T e_{vr}\\ &+ \frac{1}{2}\dot{T}_2 \dot{q}_r(t-T_2(t))^T \dot{q}_r(t-T_2(t))\end{aligned} \tag{22}$$

Considering the time derivatives of the position errors, $\dot{e}_{pl}$ and $\dot{e}_{pr}$, as follows

$$\begin{aligned}\frac{d(e_{pr})}{dt} &= \frac{d}{dt}\left(q_l(t-T_1(t)) - q_r(t)\right)\\ &= \left(1 - \frac{d}{dt}(T_1(t))\right)\dot{q}_l(t-T_1(t)) - \dot{q}_r(t)\\ &= \dot{q}_l(t-T_1(t)) - \dot{q}_r(t)\\ &\quad - \frac{d}{dt}(T_1(t))\dot{q}_l(t-T_1(t))\\ &= e_{vr} - \dot{T}_1\dot{q}_l(t-T_1(t))\\ \frac{d(e_{pl})}{dt} &= \frac{d}{dt}\left(q_r(t-T_2(t)) - q_l(t)\right)\\ &= \left(1 - \frac{d}{dt}(T_2(t))\right)\dot{q}_r(t-T_2(t)) - \dot{q}_l(t)\\ &= \dot{q}_r(t-T_2(t)) - \dot{q}_l(t)\\ &\quad - \frac{d}{dt}(T_2(t))\dot{q}_r(t-T_2(t))\\ &= e_{vl} - \dot{T}_2\dot{q}_r(t-T_2(t))\end{aligned} \tag{23}$$

we get the following relationships between $\dot{e}_{pi}$ and e_{vi}

$$\dot{e}_{pl} = e_{vl} - \dot{T}_2\dot{q}_r(t-T_2(t)) \tag{24}$$

$$\dot{e}_{pr} = e_{vr} - \dot{T}_1\dot{q}_l(t-T_1(t)) \tag{25}$$

Applying Eqs. 24 and 25 to Eq. 22, $\dot{V}$ could be simplified as becomes

$$\dot{V}=\sum_{i\epsilon\{r,l\}}\left[-\varepsilon_i^T K_i\varepsilon_i+\frac{1}{2}\varepsilon_i^T\dot{e}_{pi}+\frac{1}{2}\varepsilon_i^T e_{vi}\right.$$
$$+\frac{1}{2}e_{vi}^T\left(e_{pi}+\dot{e}_{pi}-e_{vi}\right)+\frac{1}{2}e_{pi}^T\dot{e}_{pi}$$
$$\left.-\frac{1}{2}e_{vi}^T e_{vi}-\dot{q}_i(t)^T e_{vi}\right]$$
$$+\frac{1}{2}\dot{q}_l\left(t-T_1(t)\right)^T\left(e_{vr}-\dot{e}_{pr}\right)$$
$$+\frac{1}{2}\dot{q}_r\left(t-T_2(t)\right)^T\left(e_{vl}-\dot{e}_{pl}\right)\tag{26}$$

Considering that

$$\dot{q}_l\left(t-T_1(t)\right)=e_{vr}+\dot{q}_r\tag{27}$$

$$\dot{q}_r\left(t-T_2(t)\right)=e_{vl}+\dot{q}_l\tag{28}$$

$\dot{V}$ is further simplified to

$$\dot{V}=\sum_{i\epsilon\{r,l\}}\left[-\varepsilon_i^T K_i\varepsilon_i+\frac{1}{2}\varepsilon_i^T\dot{e}_{pi}+\frac{1}{2}\varepsilon_i^T e_{vi}\right.$$
$$+\frac{1}{2}e_{vi}^T\left(e_{pi}+\dot{e}_{pi}-e_{vi}\right)+\frac{1}{2}e_{pi}^T\dot{e}_{pi}$$
$$-\frac{1}{2}e_{vi}^T e_{vi}-\dot{q}_i(t)^T e_{vi}$$
$$\left.+\frac{1}{2}\left(e_{vi}+\dot{q}_i\right)^T\left(e_{vi}-\dot{e}_{pi}\right)\right]\tag{29}$$

More simplification gives

$$\dot{V}=\sum_{i\epsilon\{r,l\}}\left[-\varepsilon_i^T K_i\varepsilon_i-\frac{1}{2}e_{vi}^T e_{vi}\right.$$
$$+\frac{1}{2}\left\{\varepsilon_i-\dot{q}_i(t)+e_{pi}\right\}^T\dot{e}_{pi}$$
$$\left.+\frac{1}{2}\left\{\varepsilon_i-\dot{q}_i(t)+e_{pi}\right\}^T e_{vi}\right]\tag{30}$$

Using the definition of ε_i in Eq. 5, negative semi-definiteness of $\dot{V}$ is seen as

$$\dot{V}=-\sum_{i\epsilon\{r,l\}}\left[\varepsilon_i^T K_i\varepsilon_i+\frac{1}{2}e_{vi}^T e_{vi}\right]\tag{31}$$

Integrating Eq. 31, it is easy to see that $V(t)-V(0)=\int_o^t\dot{V}=-\left(\int_o^t\left(\varepsilon_i^T K_i\varepsilon_i+\frac{1}{2}e_{vi}^T e_{vi}\right)\right)\leq 0$, i.e., $V(t)\leq V(0)$. Using the fact that $V(t)\geq 0$, $V(t)\leq V(0)$ and $\dot{V}(t)\leq 0$, it is possible to say that $V(t)$ is *positive bounded decreasing* function. Thus, it is concluded that all terms in $V(t)$ are bounded.

Now let us proceed to the analysis of transparency of the system by proving $\lim_{t\to\infty}e_{vi}(t)=\lim_{t\to\infty}e_{pi}(t)=0$. We will also show that $\lim_{t\to\infty}q_i(t)$ is bounded to establish closed-loop stability.

Previously, it is shown that $V(t)$ is bounded, so all terms in $V(t)$ including ε_i, $\dot{q}_i$, e_i and $\widetilde{\theta}_i\epsilon\mathcal{L}_\infty$. Using $V(t)\geq 0$ and integrating Eq. 31, $\int_o^t\left(\varepsilon_i^T K_i\varepsilon_i\right)+\frac{1}{2}\int_o^t\left(e_{vi}^T e_{vi}\right)=V(0)-V(t)\leq V(0)$, it follows that ε_i, $e_{vi}\epsilon\mathcal{L}_2$. It is easy to see from Eq. 5 that, since $\dot{q}_i\epsilon\mathcal{L}_\infty$, we have $e_{vi}\epsilon\mathcal{L}_\infty$. Combining these with Eqs. 24 and 25 and the assumption that $\dot{T}_i$ is bounded, it is seen that $\dot{e}_{pi}\epsilon\mathcal{L}_\infty$. All these bounded signals result in the boundedness of the regressor matrix Y_i, i.e., $Y_i\epsilon\mathcal{L}_\infty$. Using the boundedness of ε_i, $\widetilde{\theta}_i$, $\overline{\tau}_i$ and Y_i and Properties I and III in Eq. 9, it is seen that $\dot{\varepsilon}_i\epsilon\mathcal{L}_\infty$. Using Barbalat's lemma (see Appendix), given that $\varepsilon_i\epsilon\mathcal{L}_2$ and $\dot{\varepsilon}_i\epsilon\mathcal{L}_\infty$, it is concluded that $\lim_{t\to\infty}\varepsilon_i=0$. Using $\dot{\varepsilon}_i=\ddot{q}_i-\dot{e}_{pi}$, it is determined that $\ddot{q}\epsilon\mathcal{L}_\infty$. Invoking the time derivative of e_{vi}, e.g., $\dot{e}_{vl}=\left(1-\dot{T}_2\right)\ddot{q}_r\left(t-T_2\right)-\ddot{q}_l$, it is concluded that $\dot{e}_{vi}\epsilon\mathcal{L}_\infty$. Therefore, using Barbalat's lemma again, since $e_{vi}\epsilon\mathcal{L}_2$ and $\dot{e}_{vi}\epsilon\mathcal{L}_\infty$, it is resulted that $\lim_{t\to\infty}e_{vi}=0$. Replacing $e_{pl}=q_r\left(t-T_2(t)\right)-q_l(t)$ in $\varepsilon_l=\dot{q}_l-e_{pl}$ and using the fact that $\varepsilon_l\to 0$, stability of the system $\dot{q}_l(t)+q_l(t)=q_r\left(t-T_2(t)\right)$ can be analyzed with calculating the response of $q_l(t)$ to the $qr\left(t-T_2(t)\right)$. Homogenous response of stable differential equation $\dot{q}_l(t)+q_l(t)=q_r(t-T_2(t))$ is $q_l(t)=e^{-t}\int e^t q_r(t-T_2(t))$. Similar result could be achieved for $q_r(t)$ as $q_r(t)=e^{-t}\int e^t q_l(t-T_1(t))$. If $\int e^t q_r(t-T_2(t))$ is bounded then $q_l\to 0$, which implies that $q_r\to 0$, e_{pr} and $e_{pl}\to 0$. If

$\int e^t q_r(t-T_2(t))$ be unbounded then $q_l(t)$ would be indeterminate which could be evaluated using *Hopital*'s rule as $\lim_{t\to\infty} q_r(t) = \frac{\frac{d}{dt}\left(\int e^t q_l(t-T_1(t))\right)}{\frac{d}{dt}(e^t)} = q_l(t-T_1(t))$, $e_{pr} \to 0$. Similar results could be achieved for $e_{pl} \to 0$. Using the definition of ε_i in Eq. 5 and using the fact that $\lim_{t\to\infty} \varepsilon_i(t) = 0$ and $\lim_{t\to\infty} e_{pi}(t) = 0$, it is easy to see from Eq. 5 that $\lim_{t\to\infty} \dot{q}_i(t) = 0$ and, in other words, $\lim_{t\to\infty} q_i(t) = \text{Constant}$.

Thus, it was proved that

$$\begin{aligned}\lim_{t\to\infty} q_i(t) &= \text{Constant and } \lim_{t\to\infty} e_{vi} \\ &= \lim_{t\to\infty} e_{pi} = 0 \qquad i \in \{l, r\}\end{aligned} \tag{32}$$

□

Thus, in free motion of the bilateral telemanipulation system (1), state synchronization is satisfied under time varying communication delays. Also, the closed-loop telemanipulator is input-to-state stable from the human and environment input forces to the local and remote manipulator states.

4 Simulation Results

To verify the theoretical results of this paper, the local and remote manipulators are considered to be a pair of two-degree-of-freedom serial robots with revolute joints. The local and remote manipulator dynamics (1) have the following elements of inertia, Coriolis/centrifugal and gravity matrices:

$$\begin{aligned}M_i(q_i) &= \begin{bmatrix} M_{i_{11}} & M_{i_{12}} \\ M_{i_{21}} & M_{i_{22}} \end{bmatrix},\ C_i(q_i, \dot{q}_i) \\ &= \begin{bmatrix} C_{i_{11}} & C_{i_{12}} \\ C_{i_{21}} & C_{i_{22}} \end{bmatrix} \text{ and } G_i(q_i) = \begin{bmatrix} G_{i_1} \\ G_{i_2} \end{bmatrix}\end{aligned}$$

where for $i \varepsilon \{l, r\}$, $M_{i_{11}} = l_{i_2}^2 m_{i_2} + l_{i_1}^2 (m_{i_1} + m_{i_2}) + 2 l_{i_1} l_{i_2} m_{i_2} \cos(q_{i_2})$, $M_{i_{12}} = M_{i_{21}} = l_{i_2}^2 m_{i_2} + l_{i_1} l_{i_2} m_{i_2} \cos(q_{i_2})$, $M_{i_{22}} = l_{i_2}^2 m_{i_2}$, $C_{i_{11}} = -2 l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) \dot{q}_{i_2}$, $C_{i_{12}} = -l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) \dot{q}_{i_2}$, $C_{i_{21}} = l_{i_1} l_{i_2} m_{i_2} \sin(q_{i_2}) \dot{q}_{i_1}$, $C_{i_{22}} = 0$, $G_{i_1} = g l_{i_2} m_{i_2} \cos(q_{i_1} + q_{i_2}) + l_{i_1}(m_{i_1} + m_{i_2}) \cos(q_{i_1})$, $G_{i_2} = g l_{i_2} m_{i_2} \cos(q_{i_1} + q_{i_2})$. Here, q_{i_1} and q_{i_2} are the positions of the first and the second revolute joints, l_{i_1} and l_{i_2} are the link lengths and m_{i_1} and m_{i_2} are the masses of the first and the second links for each robot. For both manipulators, we used the same linear parameterization (see Property IV) as in [26]:

$$Y_i\left(q_i, \dot{q}_i, e_{pi}, \dot{e}_{pi}\right) = \begin{bmatrix} Y_{i_{11}} & Y_{i_{12}} & Y_{i_{13}} & Y_{i_{14}} & Y_{i_{15}} \\ Y_{i_{21}} & Y_{i_{22}} & Y_{i_{23}} & Y_{i_{24}} & Y_{i_{25}} \end{bmatrix},$$

$$\widehat{\theta}_i = \begin{bmatrix} \widehat{\theta}_{i_1} & \widehat{\theta}_{i_2} & \widehat{\theta}_{i_3} & \widehat{\theta}_{i_4} & \widehat{\theta}_{i_5} \end{bmatrix}$$

where, $Y_{i_{11}} = -\dot{e}_{pi_1}$, $Y_{i_{12}} = -2\dot{e}_{pi_1}\cos(q_{i_2}) - \dot{e}_{pi_2}\cos(q_{i_2}) + \dot{q}_{i_2} e_{pi_2} \sin(q_{i_2}) + 2 e_{pi_1} \dot{q}_{i_2} \sin(q_{i_2})$, $Y_{i_{13}} = -\dot{e}_{pi_2}$, $Y_{i_{14}} = -g\cos(q_{i_1} + q_{i_2})$, $Y_{i_{15}} = -g\cos(q_{i_1})$, $Y_{i_{21}} = 0$, $Y_{i_{22}} = -\dot{e}_{pi_1}\cos(q_{i_2}) - \dot{q}_{i_1} e_{pi_1} \sin(q_{i_2})$, $Y_{i_{23}} = -\dot{e}_{pi_1} - \dot{e}_{pi_2}$, $Y_{i_{24}} = -g\cos(q_{i_1} + q_{i_2})$, $Y_{i_{25}} = 0$ and $\widehat{\theta}_{i_1} = \widehat{l_{i_2}^2}\widehat{m}_{i_2} + \widehat{l_{i_1}^2}(\widehat{m}_{i_1} + \widehat{m}_{i_2})$, $\widehat{\theta}_{i_2} = \widehat{l}_{i_1}\widehat{l}_{i_2}\widehat{m}_{i_2}$, $\widehat{\theta}_{i_3} = \widehat{l_{i_2}^2}\widehat{m}_{i_2}$, $\widehat{\theta}_{i_4} = \widehat{l}_{i_2}\widehat{m}_{i_2}$, $\widehat{\theta}_{i_5} = \widehat{l}_{i_1}(\widehat{m}_{i_1} + \widehat{m}_{i_2})$, $i \epsilon \{l, r\}$.

Using the above definitions for the elements of the matrix $\widehat{\theta}_i$, it is possible to estimate matrices M_i, C_i and G_i based on the elements of $\widehat{\theta}_i$ that will be estimated online.

In simulations, the physical parameters of the manipulators are set to $m_{l_1} = 4\ kg$, $m_{l_2} = 0.5\ kg$, $l_{l_1} = 50\ cm$, $l_{l_2} = 50\ cm$, $m_{r_1} = 3.4\ kg$, $m_{r_2} = 0.25\ kg$, $l_{r_1} = 50\ cm$, $l_{r_2} = 50\ cm$ and the controller gain K_i is set to $3I$. In the following, three simulation scenarios are considered involving constant time delays, random time delays and sinusoidal time delays (scenarios A, B and C, respectively). A human torque, which is shown in Fig. 2, is applied to the local manipulator and the tracking performance of the first and the second joints of the local and remote manipulators are considered.

4.1 Simulation with Constant Time Delays

In Fig. 3, simulation results for a constant time delay similar to that used in [26], $T_1 = 0.4$ and $T_2 = 0.4$ seconds, in terms of joint positions of the remote manipulator and delayed joint positions of the local manipulator in the presences of the exerted human torque are shown. Comparing the results, it can be seen that the results of the proposed scheme is exactly the same as that of [26]. This similarity is because of the fact that in this simulation time delays are constant.

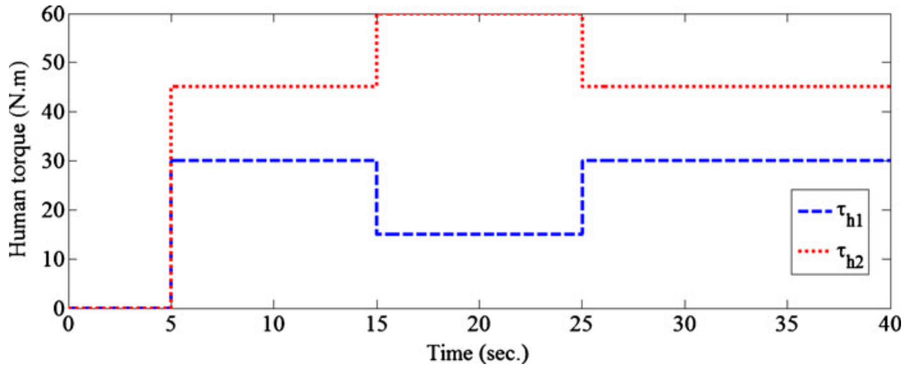


Fig. 2 Exerted human torque

4.2 Simulation with Random Time Delays

In this part, simulation results of the proposed controller compared with [26] for random time delays with Gaussian distribution with mean 0.48 second and standard deviation of 0.022, are shown. In this simulation, again the positions of the first and the second joints of the remote manipulator compared with delayed joint positions of the local manipulator in the presences of exerted human torque are shown. As it can be seen from Fig. 4, the proposed scheme has better tracking performance and less fluctuations and settling time than the controller [26].

4.3 Simulation with Sinusoidal Time Delays

Let us verify the telemanipulator's free motion tracking performance under sinusoidal time varying delays. The feedforward and feedback delays in the communication channel are assumed to

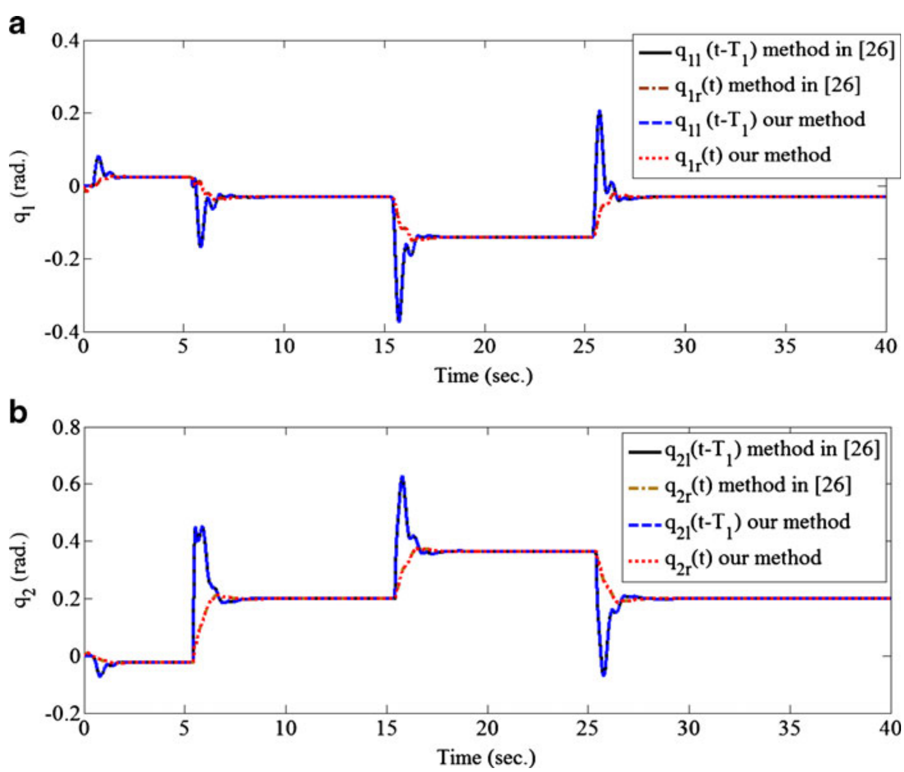


Fig. 3 **a** Positions of the first joints of the local and remote manipulator in telemanipulation with constant time delay. **b** Positions of the second joints of the local andremote manipulator in telemanipulation with constant time delay

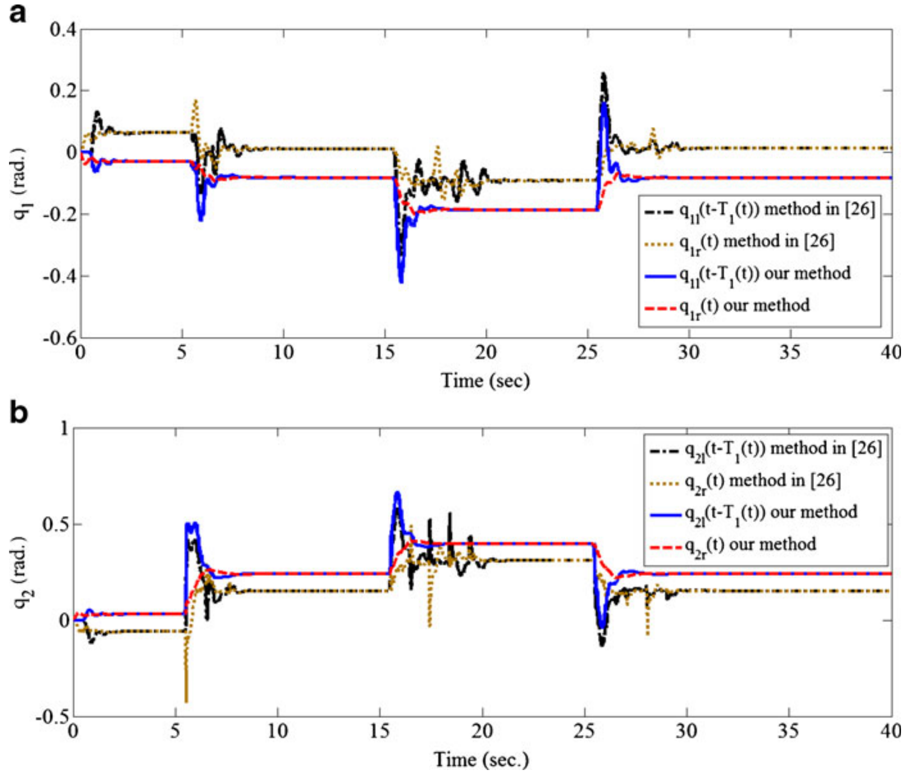


Fig. 4 **a** Positions of the first joints of the local and remote manipulators in telemanipulation with random time delay. **b** Positions of the second joints of the local and remote manipulators in telemanipulation with random time delay

be changing as sinusoids with a mean of 1 second and frequencies of 0.5027 and 0.4714 rad/sec – see Fig. 5.

Joint positions of the local and the remote manipulators in the presences of the exerted human torque of Fig. 2 are shown in Fig. 6. It is remarkable that state synchronization of the bilateral teleoperation system is satisfied in the presence of the fast varying communication delays. In Fig. 7, tracking errors in the first and the second joints of the local and remote manipulators are shown, which are asymptotically converging to zero as predicted by the theory.

As shown in Figs. 3, 4 and 6, after a command is being applied to the local robot, a couple of seconds of settling time is needed to achieve synchronization between the local and the remote robots. This settling time depends on the values of the constant time delay (Fig. 3) or the varying time delay (Figs. 4 and 6). Considering these figures,

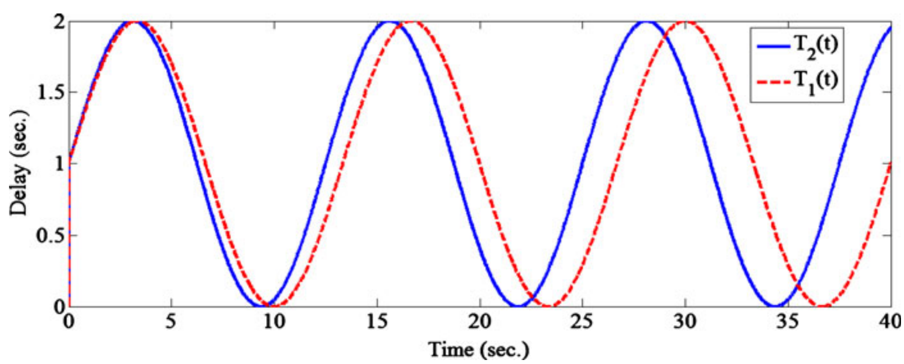


Fig. 5 Time varying delays in communication channel

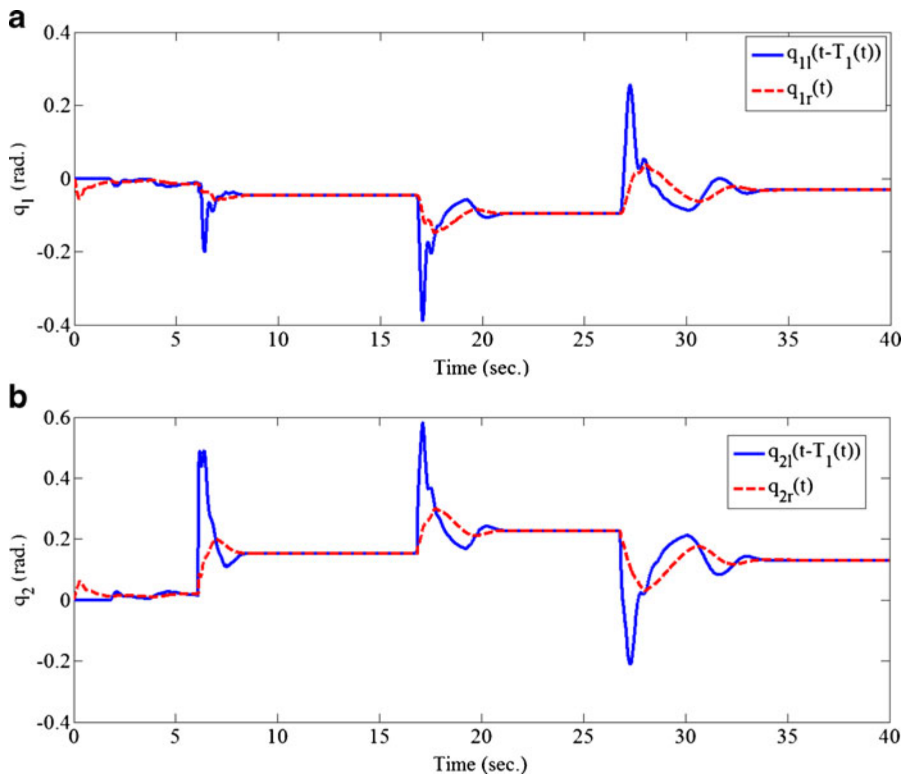


Fig. 6 **a** Positions of the first joints of the local and remote manipulators in telemanipulation with sinusidal time varying delay. **b** Positions of the second joints of the local and remote manipulators in telemanipulation with sinusidal time varying delay

the proposed adaptive controller is able to handle time varying delays and guarantee asymptotic synchronization between the local and the remote robots as opposed to prior art [26], which is only meant for constant time delays.

If we apply the controller in [26] to the same local and remote robots with the same sinusoidal delays in the communication channel, instability happens in the local and the remote manipulators as shown in Fig. 8.

5 Experimental Results

To verify the theoretical results of this paper, the local and the remote manipulators are considered to be two PHANToM Omni robots (Sensable Technologies, Inc., Wilmington, MA) as shown in Fig. 9. The utilized PHANToM robots are three degree of freedom robots that map the generalized joint angles of the robot (q_1, q_2 and q_3) to the Cartesian position (X, Y and Z) of

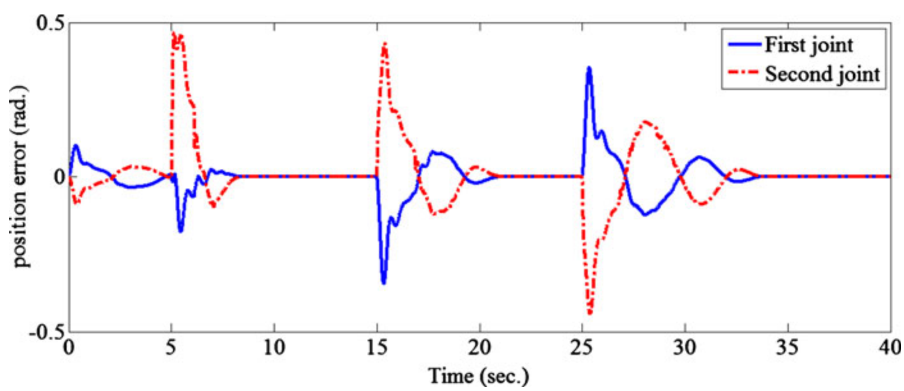
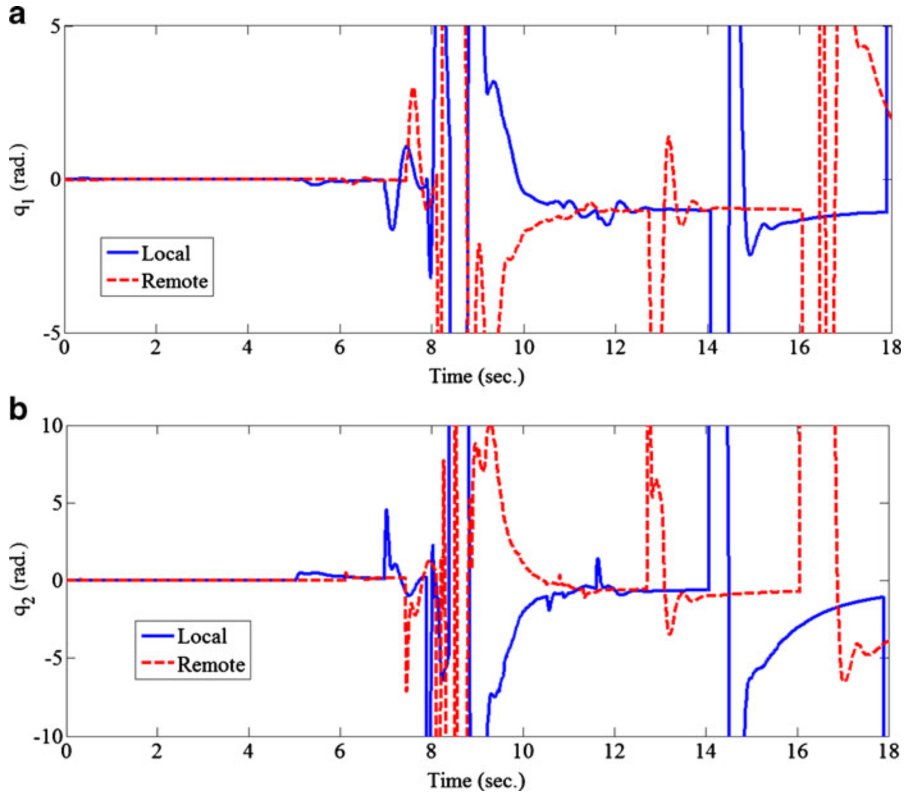


Fig. 7 Tracking errors of the positions of the first and second joints between the local and the remote manipulators

Fig. 8 **a** Positions of the first joints of the local and remote manipulators with controller in [26] with sinusidal time varying delay. **b** Positions of the second joints of the local and remote manipulators with controller in [26] with sinusidal time varying delay



the gimbal. These local and remote robots are connected to the computer using 1394 ports. As the human operator moves the local robot, the remote robot which is in free motion follows the state of the local robot. Controllers for the local and the remote robots are implemented based on Eqs. 2–5. To artificially create varying time delays between the local and the remote robots, a first-input, first-output circular buffer is used for each robot – changing the length of these buffers create time-varying time delays in the communication channel.

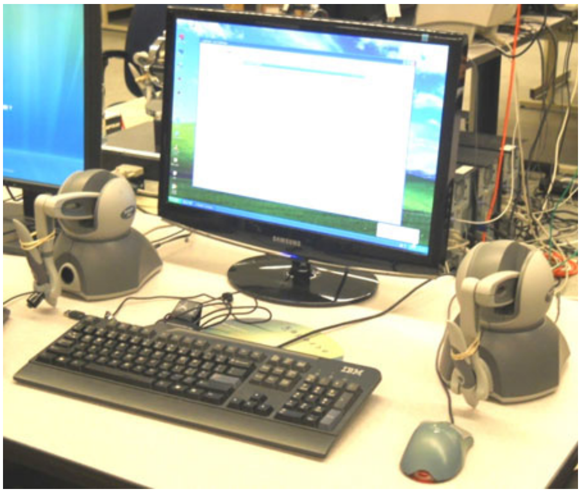


Fig. 9 Teleoperation system with two PHANToM Haptic devices

The schematics of PHANToM robot with its corresponding joint angles are shown in Fig. 10.

The local and remote PHANToM dynamics (1) have the following elements of inertia, Coriolis/centrifugal and gravity matrixes:

$$M_i(q_i) = \begin{bmatrix} M_{i_{11}} & M_{i_{12}} & M_{i_{13}} \\ M_{i_{21}} & M_{i_{22}} & M_{i_{23}} \\ M_{i_{31}} & M_{i_{32}} & M_{i_{33}} \end{bmatrix},$$

$$C_i(q_i, \dot{q}_i) = \begin{bmatrix} C_{i_{11}} & C_{i_{12}} & C_{i_{13}} \\ C_{i_{21}} & C_{i_{22}} & C_{i_{23}} \\ C_{i_{31}} & C_{i_{32}} & C_{i_{33}} \end{bmatrix} \text{ and } G_i(q_i) = \begin{bmatrix} G_{i_1} \\ G_{i_2} \\ G_{i_3} \end{bmatrix}$$

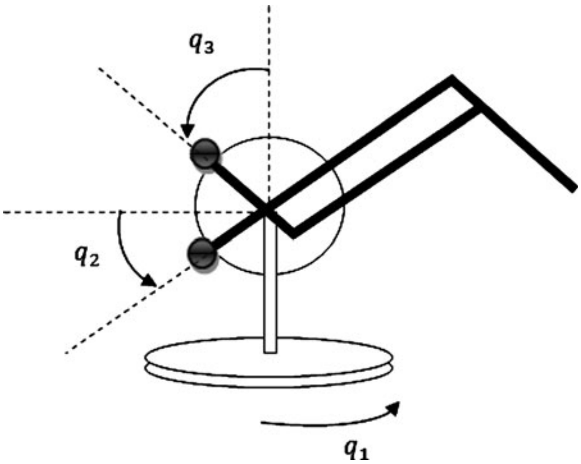


Fig. 10 Schematics of PHANToM robot with its corresponding joint angles

where for $i \epsilon \{l, r\}$, $M_i(q_i)$, $C_i(q_i, \dot{q}_i)$ and $G_i(q_i)$ defined in terms of kinematic and inertial properties of the PHANToM [29].

The linear parameterization of the PHANToM (see Property IV) is reported in [30]. We use a similar parameterization, Eq. 7, as:

$$Y_i\left(q_i, \dot{q}_i, e_{pi}, \dot{e}_{pi}\right) = \begin{bmatrix} Y_{i_{11}} & Y_{i_{12}} & Y_{i_{13}} & Y_{i_{14}} & Y_{i_{15}} & Y_{i_{16}} & Y_{i_{17}} & Y_{i_{18}} \\ Y_{i_{21}} & Y_{i_{22}} & Y_{i_{23}} & Y_{i_{24}} & Y_{i_{25}} & Y_{i_{26}} & Y_{i_{27}} & Y_{i_{28}} \\ Y_{i_{31}} & Y_{i_{32}} & Y_{i_{33}} & Y_{i_{34}} & Y_{i_{35}} & Y_{i_{36}} & Y_{i_{37}} & Y_{i_{38}} \end{bmatrix}$$

$$\widehat{\pi}_i = \left[\, \widehat{\pi}_{i_1}\ \widehat{\pi}_{i_2}\ \widehat{\pi}_{i_3}\ \widehat{\pi}_{i_4}\ \widehat{\pi}_{i_5}\ \widehat{\pi}_{i_6}\ \widehat{\pi}_{i_7}\ \widehat{\pi}_{i_8} \,\right]$$

where, $Y_{i_{11}} = \dot{e}_{pi_1}$, $Y_{i_{12}} = \dot{e}_{pi_1} c_{i_{2.2}} - 2e_{pi_1} \dot{q}_{i_2} s_{i_2} c_{i_2} - \dot{q}_{i_1} e_{pi_2} s_{i_{2.2}}$, $Y_{i_{13}} = \dot{e}_{pi_1} c_{i_{2.3}} - 2e_{pi_1} \dot{q}_{i_3} s_{i_3} c_{i_3} - \dot{q}_{i_1} e_{pi_3} s_{i_{2.3}}$, $Y_{i_{14}} = \dot{e}_{pi_1} c_{i_2} s_{i_3} - \frac{1}{2}(e_{pi_1} \dot{q}_{i_2} + \dot{q}_{i_1} e_{pi_2}) s_{i_2} s_{i_3} + \frac{1}{2}(e_{pi_1} \dot{q}_{i_3} + \dot{q}_{i_1} e_{pi_3}) c_{i_2} c_{i_3}$, $Y_{i_{15}} = 0$, $Y_{i_{16}} = 0$, $Y_{i_{17}} = 0$, $Y_{i_{18}} = 0$, $Y_{i_{21}} = 0$, $Y_{i_{22}} = \dot{q}_{i_1} e_{pi_1} s_{i_{2.2}}$, $Y_{i_{23}} = 0$, $Y_{i_{24}} = -\frac{1}{2} \dot{e}_{pi_3} s_{i_{23}} + \frac{1}{2} \dot{q}_{i_1} e_{pi_1} s_{i_2} s_{i_3} + \frac{1}{2} \dot{q}_{i_3} e_{pi_3} c_{i_{23}}$, $Y_{i_{25}} = \dot{e}_{pi_2}$, $Y_{i_{26}} = 0$, $Y_{i_{27}} = c_{i_2}$, $Y_{i_{28}} = 0$, $Y_{i_{31}} = 0$, $Y_{i_{32}} = 0$, $Y_{i_{33}} = \dot{q}_{i_1} e_{pi_1} s_{i_{2.3}}$, $Y_{i_{34}} = -\frac{1}{2} \dot{e}_{pi_2} s_{i_{23}} - \frac{1}{2} \dot{q}_{i_1} e_{pi_1} c_{i_2} c_{i_3} + \frac{1}{2} \dot{q}_{i_2} e_{pi_2} c_{i_{23}}$, $Y_{i_{35}} = 0$, $Y_{i_{36}} = \dot{e}_{pi_3}$, $Y_{i_{37}} = 0$, $Y_{i_{38}} = s_{i_3}$ and $\widehat{\pi}_i$ is same as reported in [30]. In the elements of matrix Y_i, s_{i_m}, c_{i_m}, $s_{i_{mn}}$, $c_{i_{mn}}$, $s_{i_{2,m}}$ and $c_{i_{2,m}}$, m, $n = 1, 2, 3$, stands for $\sin(q_{i_m})$, $\cos(q_{i_m})$, $\sin(q_{i_m} - q_{i_n})$, $\cos(q_{i_m} - q_{i_n})$, $\sin(2q_{i_m})$, $\cos(2q_{i_m})$ respectively.

Let us verify the PHANToM's free motion tracking performance under sinusoidal time varying delays. The feedforward and feedback delays in the communication channel are assumed to be changing as sinusoids with a mean of 0.2 s. Joint positions of the local and the remote PHANToM robots are shown in Fig. 11. It is remarkable that state synchronization of the bilateral teleoperation system is satisfied in the presence of the varying communication delays.

To compare the experimental tracking performance of the proposed controller with the controller in [26], experimental results corresponding

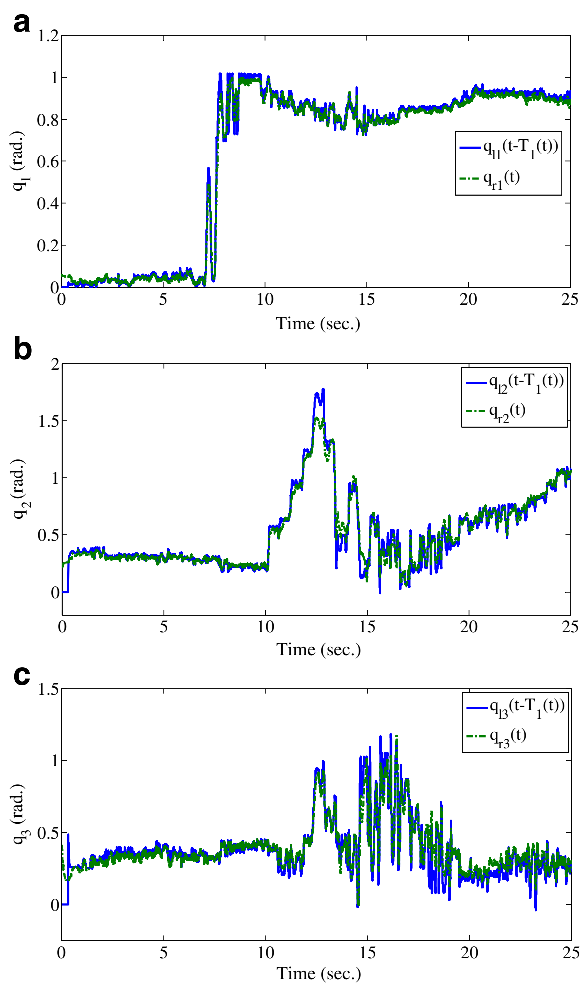


Fig. 11 **a** Positions of the first joints of the local and remote PHANToM robots in telemanipulation with sinusoidal time varying delay. **b** Positions of the second joints of the local and remote PHANToM robots in telemanipulation with sinusoidal time varying delay. **c** Positions of the third joints of the local and remote PHANToM robots in telemanipulation with sinusoidal time varying delay

to the controller in [26] being used with the same two PHANToM robots in the presence of varying time delays are demonstrated in Fig. 12. It is evident from Fig. 12 that instability happens in the teleoperation in the presence of time varying delay when the controller in [26] is used.

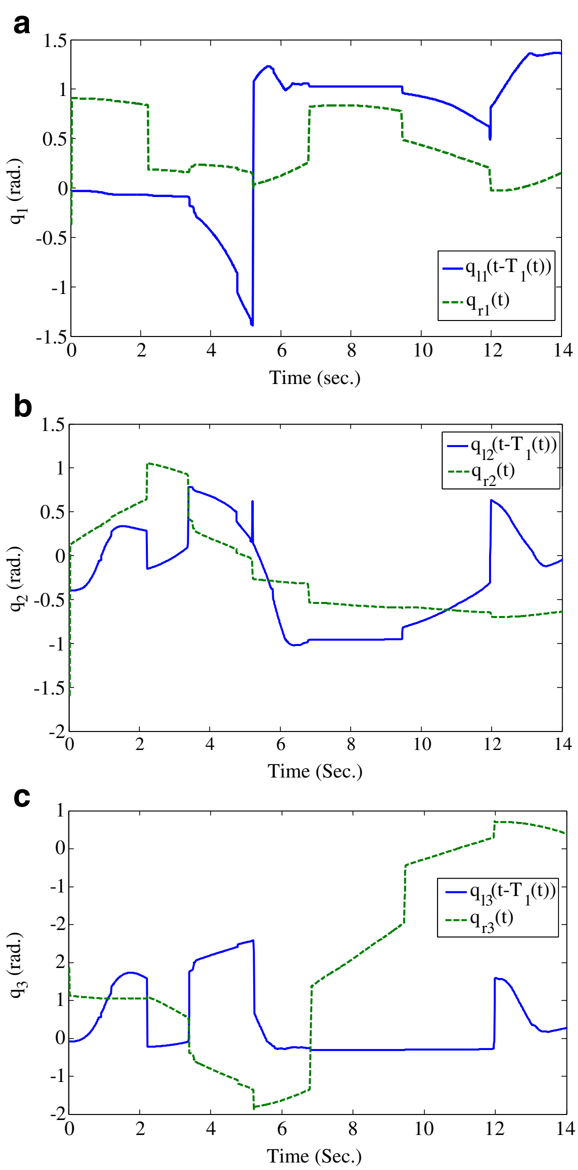


Fig. 12 **a** First joint position tracking between the local and the remote robots during teleoperation using the controller in [26]. **b** Second joint position tracking between the local and remote robots during teleoperation using the controller in [26]. **c** Third joint position tracking between the local and remote robots during teleoperation using the controller in [26]

6 Conclusion and Future Work

In this paper, a new state synchronizing controller for bilateral teleoperation systems with varying time delays in the communication channel is proposed. Lyapunov stability of the closed-loop system in the presence of time varying delays is established. Besides, it is proved and also shown via simulations that using the proposed controller, asymptotic synchronization between the local and the remote robots occurs. The proposed controller entails adaptive tuning rules in the local and the remote sides to estimate the unknown/uncertain dynamic parameters of the manipulators. Thus, only the estimated values of the robots' parameters are needed in the controller when providing for the asymptotic state synchronization between the local and the remote robots under varying time delays. As future work, state synchronization under varying time delays during contact-motion telemanipulation with consideration for force tracking to obtain full transparency will be studied.

Appendix

1. If $f(t) \in \mathcal{L}_2$, then there exist a positive constant M such that $\int |f(t)|^2 \, dt < M$. This implies that f is Riemann integrable.
2. If $\dot{f}(t) \in \mathcal{L}_\infty$, then f is uniformly continuous.

Barbalat's lemma says that if function $f : \mathrm{R}^+ \to \mathrm{R}^+$ is *uniformly continuous* and be Riemann integrable, then $\lim_{t\to\infty} f(t) = 0$.

References

1. Kuan, C.-P., Young, K.: VR-based teleoperation for robots compliance control. J. Intell. Robot. Syst. **30**(4), 377–398 (2001)
2. Baier, H., Schmidt, G.: Transparency and stability of bilateral kinesthetic teleoperation with time-delayed

communication. J. Intell. Robot. Syst. **40**(1), 1–22 (2004)
3. Alfi, A., Farrokhi, M.: Force reflecting bilateral control of master-slave systems in teleoperation. J. Intell. Robot. Syst. **52**(2), 209–232 (2008)
4. Nitzsche, N., Schmidt, G.: Force-reflecting telepresence in extensive remote environment. J. Intell. Robot. Syst. **50**(1), 3–18 (2007)
5. Sheridan, T.B.: Space teleoperation through time delay: review and prognosis. IEEE Trans. Robot. Autom. **9**(5), 592–606 (1993)
6. Hannaford, B.: A design framework for teleoperators with kinesthetic feedback. IEEE Trans. Robot. Autom. **5**(4), 426–434 (1989)
7. Imaida, T., Yokokohji, Y., Doi, T., Oda, M., Yoshikawa, T.: Groundspace bilateral teleoperation of ETS-VII robot arm by direct bilateral coupling under 7-s time delay condition. IEEE Trans. Robot. Autom. **20**(3), 499–511 (2004)
8. Anderson, R.J., Spong, M.W.: Asymptotic stability for force reflecting teleoperations with time delay. In: IEEE International Conference on Robotics and Automation, pp. 1618–1625 (1989)
9. Niemeyer, G., Slotine, J.J.E.: Stable adaptive teleoperation. IEEE J. Ocean. Eng. **16**, 152–162 (1991)
10. Niemeyer, G., Slotine, J.J.E.: Telemanipulation with time delays. Int. J. Robot. Res. **23**(9), 873–890 (2004)
11. Lozano, R., Chopra, N., Spong, M.W.: Passivation of force reflecting bilateral teleoperators with time varying delay. In: Proceedings of the 8. Mechatronics Forum, pp. 954–962 (2002)
12. Leeraphan, S., Maneewan, T., Laowattana, S.: Stable adaptive bilateral control of transparent teleoperation through time-varying delay. In: Proceeding of the International Conference on Intelligent Robots and Systems, vol. 3, pp. 2979–2984 (2002)
13. Lee, D., Spong, M.W.: Passive bilateral control of teleoperators under constant time delay. IEEE Trans. Robot. **22**(2), 269–281 (2006)
14. Aziminejad, A., Tavakoli, M., Patel, R.V., Moallem, M.: Stability and performance in delayed bilateral teleoperation: theory and experiments. Control Eng. Pract. **16**(11), 1329–1343 (2008)
15. Aziminejad, A., Tavakoli, M., Patel, R.V., Moallem, M.: Transparent time-delayed bilateral teleoperation using wave variables. IEEE Trans. Control Syst. Technol. **16**(3), 548–555 (2008)
16. Desoer, C.A., Vidyasagar, M.: Feedback Systems: Input–Output Properties. Academic Press, New York (1975)
17. Hokayem, P.F., Spong, M.W.: Bilateral teleoperation: an historical survey. Automatica **42**(12), 2035–2057 (2006)
18. Hosseini-Suny, K., Momeni, H., Janabi-Sharifi, F.: Model reference adaptive control design for a teleoperation systems with output prediction. J. Intell. Robot. Syst. **59**(3–4), 319–339 (2010)
19. Chopra, N., Spong, M.W.: Passivity-based control of multi-agent systems. In: Advances in Robot Control: from Everyday Physics to Human-Like Movements, pp. 107–134. Springer, Berlin (2006)
20. Lee, D.J., Spong, M.W.: Passive bilateral teleoperation with constant time delay. IEEE Trans. Robot. **22**(2), 269–281 (2006)
21. Niemeyer, G., Slotine, J.J.E.: Towards force-reflecting teleoperation over the internet. In: Proceeding of International Conference on Robotics and Automation, pp. 1909–1915 (1997)
22. Gu, Y., Zhang, C., Chong, K.T.: Adaptive passive control with varying time delay. Simul. Model. Pract. Theory **18**(1), 1–8 (2010)
23. Nuño, E., Basañez, L., Ortega, R.: Passivity-based control for bilateral teleoperation: a tutorial. Automatica **47**(3), 485–495 (2011)
24. Chopra, N., Spong, M.W.: On synchronization of networked passive systems with time delays and application to bilateral teleoperation. In: Proceeding of Society of Instrument and Control Engineers of Japan (2005)
25. Angeles, A.R., Nijmeijer, H.: Mutual synchronization of robots via estimated state feedback: a cooperative approach. IEEE Trans. Control Syst. Technol. **12**, 542–554 (2004)
26. Nuño, E., Ortega, R., Basañez, L.: An adaptive controller for nonlinear teleoperators. Automatica **46**(1), 155–159 (2010)
27. Kelly, R., Santibáñez, V., Loria, A.: Control of Robot Manipulators in Joint Space. Springer, Berlin (2005)
28. Spong, M.W., Hutchinson, S., Vidyasagar, M.: Robot Modeling and Control. Wiley (2006)
29. Cavusoglu, M.C., Feygin, D., Tendick, F.: A critical study of the mechanical and electrical properties of the phantom haptic interface and improvements for high performance control. Presence-Teleop. Virt. Environ. **11**, 555–568 (2002)
30. Tahmasebi, A.M., Taati, B., Mobasser, F., Hashtrudi-Zaad, K.: Dynamic parameter identification and analysis of a PHANToM haptic device. In: Proceedings of IEEE Conference on Control Applications, pp. 1251–1256 (2005)