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Position and Force Control of Bilateral Teleoperation Systems With Time-varying Delays Based on Force Estimation

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Abstract: A position and force tracking control based on force estimation is proposed for bilateral teleoperation systems with time-varying delays. A time-delay state observer is employed to estimate the system state variables affected by the delays. To estimate the interaction forces effectively, a force estimation algorithm with adaptive law is designed. Based on the estimated states and forces, a P+D controller is designed to simultaneously guarantee the position and force tracking of the system. The stability and tracking performance of the closed-loop system are proved via Lyapunov functions, and the feasibility of the proposed control is verified by both simulations and experiments. The proposed control can improve the position and force tracking performance of bilateral teleoperation systems under time-varying delays. Meanwhile, it neither requires force measurement nor the bound of the derivative of the time-varying delays to be within one.

Keywords: Bilateral teleoperation systems, force estimation algorithm, force tracking, position tracking, time-delay state observer.

1. INTRODUCTION

Teleoperation systems have aroused wide attentions and become an attractive research area in robotic applications. In a teleoperation system, the operator remotely controls the slave robot through the master robot, replacing humans to perform tasks in complex and special environments, such as radioactive and hazardous materials handling, underwater exploration, space operation and remote surgery [1-4]. The operator information is passed to the slave through the master, then the environment information in turn is passed to the master through the slave. Since the information of the master and slave needs to be transformed on both sides, this is called bilateral teleoperation systems (BTSs) [5]. In BTSs, the operator can perceive the interaction force between the slave and the remote environment as if he is directly interacting with the environment, thus improving the operator's task performance in remote operations. However, there are two significant challenges that the BTSs mainly face, including unknown time-varying delays and the impact of the interaction forces on system performance.

When the information is transformed between the master and slave in BTSs, the communication delays as one of the complex practical problems is inevitable. Therefore, the communication delays cannot be ignored in the control loop. Although many researches have been conducted on the control of BTSs with constant communication delays, the most common delays are time-varying rather than constant in practice. In [6], an improved negative feedback controller was designed using passivity to ensure that the BTSs were stable with time-varying delays. In [7], a controller based on motion prediction was designed for BTSs with time-varying delays. The predictor consisted of several sub-predictors each of which was used to predict the state of the previous predictor. However, in [6,7] it is required that the derivative of the time-varying delays (i.e., the rate of change of the time-varying delays) should be less than one in order to guarantee the stability of the BTSs, which is a limitation in practice. In most teleoperation systems, the time-varying delays are usually unknown and the derivative of the time-varying delays cannot be always limited within one, and probably it will exceed one. In [8], a finite-time adaptive control scheme based on the combination of position error and force error was proposed when the BTSs is affected by time-varying delays and model uncertainties. In [9], an observer was used to estimate the system state variables for the BTSs with time-varying delays, which ensured that the salve could accurately track the position of the master. It

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should be noted that although the derivative of the time-varying delays is not required to be less than one in [8,9], they can only guarantee the position tracking performance between the master and slave but not the force tracking performance.

In addition to communication delays, the interaction forces (i.e., the interaction force between the operator and the master, and the interaction force between the slave and the environment) also affect the teleoperation system performance. Particularly, in some precise teleoperations such as beating heart surgery, inaccurate interaction forces may degrade system performance and even cause the system unstable [10-12]. However, the use of force sensors, in turn, faces some problems such as high cost, low accuracy, difficult parameter-setting, and sensitive to noise. Moreover, the complex work environment of teleoperation makes it undesirable to measure the interaction forces through existing force sensors [13]. To avoid measuring force signals, different force estimation algorithms have been proposed. In [14], an observer with unknown inputs was proposed to estimate the interaction forces for the BTSs with time delays. In [15], a passive control strategy based on passivity was designed for the BTSs with time delays. In [16], the interaction forces of the teleoperation systems with model uncertainty and time delay were estimated by nonlinear disturbance observer. In [17], the robustness of uncertain nonlinear BTSs with time-varying delays was enhanced by adding an auxiliary variable, and an adaptive torque observer was applied to avoid the utilization of force sensors. In [14-17], the position tracking between the master and slave can be guaranteed and force sensors can be avoided through estimating the interaction forces. Nevertheless, the force tracking performance of the system cannot be guaranteed in [14-17].

To guarantee the tracking performance while avoiding the use of sensors to obtain the interaction forces, in [18] an adaptive bilateral teleoperation scheme based on sliding-mode-assisted observer was proposed. The direct measurement of force was replaced by the observer to ensure the position and force tracking of the BTSs. In [19], a force-position control based on nonlinear observer was investigated for the BTSs with constant communication delays. In [20], for the BTSs with constant communication delays, an improved force estimation algorithm was designed to avoid measuring the interaction forces. However, it should be noted that in [18] the communication delays were not considered, while in [19,20] only constant communication delays were considered rather than time-varying delays.

From the above recent work, some questions naturally come to our mind: For BTSs with time-varying delays, how to simultaneously ensure the position and force tracking? How to avoid the direct measurement of the interaction forces? And how to relieve the constraint on the derivative of the time-varying delays? Therefore, this paper proposes a position and force tracking control based on force estimation for bilateral teleoperation systems with time-varying delays. The main contributions of this paper are as follows:

1) A force estimation algorithm is designed to obtain the estimations of the human force and the environment force, which replaces the measurement of interaction forces.
2) Based on the estimated state variables obtained by time-delay state observer (TDSO) and the estimated interaction forces obtained by force estimation algorithm, a P+D controller is designed to simultaneously ensure the position and force tracking performance when the system is subjected to time-varying delays.
3) The stability and tracking performance of the BTSs can be guaranteed without constraining the bound of the derivative of the time-varying delays within one.
4) The proposed control method can reduce the impact of time-varying delays on the position and force tracking while avoiding the use of force sensors in BTSs.

2. DYNAMIC MODEL OF BILATERAL TELEOPERATION SYSTEMS

In the BTSs, the nonlinear dynamics of the master and slave robots with n-degree of freedom are modeled as [20]

$$M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + G_m(q_m) = \tau_h - \tau_m, \tag{1}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G_s(q_s) = \tau_s - \tau_e, \tag{2}$$

where the subscript $i \in \{m, s\}$ represents the master and slave, q_i, $\dot{q}_i$, $\ddot{q}_i \in R^n$ are the joint position, joint velocity and joint acceleration, respectively. Besides, $M_i(q) \in R^{n\times n}$, $C_i(q,\dot{q}) \in R^{n\times n}$, $G_i(q) \in R^n$ are the symmetric positive definite inertia matrix, the Coriolis/centrifugal matrix, and the gravitational vector, respectively. Also, $\tau_i \in R^n$ is the control torque, $\tau_h \in R^n$ is the interaction force between the operator and the master (also called the human force), and $\tau_e \in R^n$ is the interaction force between the slave and the environment (also called the environment force), respectively. For brevity we will write $M_i(q)$ as M_i, $C_i(q,\dot{q})$ as C_i, and $G_i(q)$ as G_i hereafter, respectively.

There are some important properties for the dynamic model (1) and (2) [21]

Property 1: The relationship between the Coriolis/centrifugal matrix and the inertia matrix of the robot is

$$\dot{M}_i = C_i + C_i^T. \tag{3}$$

Property 2: The symmetric positive definite inertia matrix has upper and lower bounds, i.e., $0 < \lambda_{\min}(M_i)I < M_i < \lambda_{\max}(M_i)I < \infty$, where I denotes the unit matrix, λ_{min}

and λ_{max} denotes the maximum and minimum eigenvalues of the matrix, respectively.

Property 3: There exists a bounded positive number υ such that the Coriolis/centrifugal matrix C_i satisfies

$$\|C_i(q_i,X)Y\|_2 \le \upsilon\|X\|_2\|Y\|_2, \tag{4}$$

where X and Y are vector functions of the same dimension as C_i.

3. DESIGN OF CONTROL METHOD

The framework of the proposed position and force control method based on force estimation is shown in Fig. 1. Consider the BTSs with time-varying delays $d_m(t)$ in the forward communication and $d_s(t)$ in the backward communication. First, the TDOS is employed to estimate the system state variables affected by the delays $q_i(t-d_i(t))$and obtain the estimation $\hat{q}_i(t-d_i(t))$. Next, the force estimation algorithm is designed to obtain the estimation of the interaction forces $\hat{\tau}_h$ and $\hat{\tau}_e$, respectively, avoiding the directly use of force sensors in complex environments. Finally, the master and slave controllers are designed based on the estimated states and estimated forces to simultaneously achieve the position and force tracking of the system.

4. TIME-DELAY STATE OBSERVER

Consider the communication delays are unknown, unmeasured, asymmetric and time-varying. Let's define $d_m(t)$ is the forward communication delay from the master to the slave and $d_s(t)$ is the backward communication delay from the slave to the master. Then there exists a positive constant D_i such that $d_i(t)$ satisfies

$$0 \le d_i(t) \le D_i. \tag{5}$$

Since the derivative of the time-varying delays is usually unknown and immeasurable, time-delay state observer

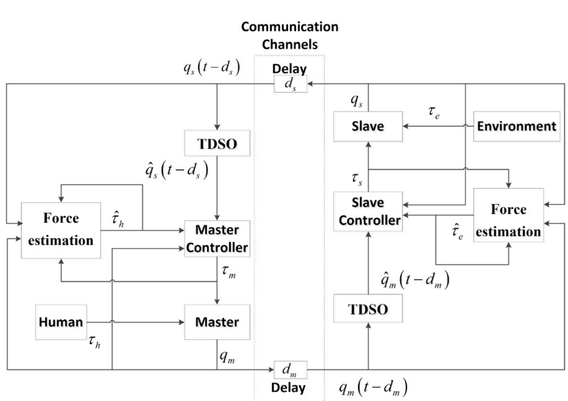


Fig. 1. Framework of the proposed position and force tracking control method based on force estimation.

(TDSO) is used to obtain the state variables affected by the time-varying delays. The TDSO is designed as

$$\dot{Z}_{i1}(t) = Z_{i2}(t) - \chi_{i1}\left(Z_{i1}(t) - X_{i1}(t)\right), \tag{6}$$
$$\dot{Z}_{i2}(t) = -\chi_{i2}\left(Z_{i1}(t) - X_{i1}(t)\right), \tag{7}$$

where the subscript $i \in \{m, s\}$ also represents the master and slave, respectively. The state variables $X_{i1}(t) = q_i(t - d_i(t))$ and $X_{i2}(t) = \dot{q}_i(t-d_i(t))$ denote the position and velocity affected by the time-varying delays, respectively. Besides, $Z_{i1}(t)$ is the estimation of $X_{i1}(t)$, and $Z_{i2}(t)$ is the estimation of $X_{i2}(t)$, i.e., $\hat{q}_i(t-d_i(t)) = \hat{X}_{i1}(t) = Z_{i1}(t)$, $\hat{\dot{q}}_i(t-d_i(t)) = \hat{X}_{i2}(t) = Z_{i2}(t)$. Also, χ_{i1} and χ_{i2} are constant gains of the observer.

The position and velocity estimation errors are defined as

$$e_{i1} = Z_{i1}(t) - X_{i1}(t), \tag{8}$$
$$e_{i2} = Z_{i2}(t) - X_{i2}(t). \tag{9}$$

Differentiating (8) and (9) with respect to time and substituting (6) and (7) into them, the observer error system can be given by

$$\dot{e}_{i1} = \dot{Z}_{i1}(t) - \dot{X}_{i1}(t) = e_{i2} - \chi_{i1}e_{i1}, \tag{10}$$
$$\dot{e}_{i2} = \dot{Z}_{i2}(t) - \dot{X}_{i2}(t) = -\dot{X}_{i2}(t) - \chi_{i2}e_{i1}. \tag{11}$$

Further, the observer error system (10)-(11) can be rewritten as

$$\dot{e}_{Ti}(t) = Le_{Ti}(t) + Nh(t), \tag{12}$$

where $L = \begin{bmatrix} -\chi_{i1} & 1 \\ -\chi_{i2} & 0 \end{bmatrix}$,$N = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$,$e_{Ti}(t) = \begin{bmatrix} e_{i1}(t) \\ e_{i2}(t) \end{bmatrix}$, and $h(t) = \begin{bmatrix} 0 \\ -\dot{X}_{i2}(t) \end{bmatrix}$.

Since there exists an upper bound $\dot{X}_{i2}(t) \le W$ for $\dot{X}_{i2}(t)$, it has $\|h(t)\| \le W$ [22]. Moreover, there exist constant gains $\chi_{i1} > 0$ and $\chi_{i2} > 0$ such that $L^TP + PL = -Q$, where Q is a positive definite matrix and

$$P = \begin{bmatrix} \chi_{i1}^2 + \chi_{i2}^2 & -\chi_{i2} \\ -\chi_{i2} & 2 \end{bmatrix}. \tag{13}$$

Theorem 1: For the BTSs (1) and (2) subjected to time-varying delays, if the position $X_{i1}(t)$ and velocity $X_{i2}(t)$ affected by time-varying delays are observed by the TDSOs (6) and (7), then the position and velocity estimation error $e_{Ti}(t)$ is bounded.

Proof: Consider a Lyapunov function as

$$V_t(t) = e_{Ti}^T(t)Pe_{Ti}(t). \tag{14}$$

Substituting (12) into the time derivative of (14), we can get

$$\dot{V}_t(t) = \dot{e}_{Ti}^T(t)Pe_{Ti}(t) + e_{Ti}^T(t)P\dot{e}_{Ti}(t)$$

$$
\begin{aligned}
&= 2e_{Ti}^T(t)PNh(t) \\
&\quad + e_{Ti}^T(t)\left(L^TP + PL\right)e_{Ti}(t) \\
&= 2e_{Ti}^T(t)PNh(t) - e_{Ti}^T(t)Qe_{Ti}(t).
\end{aligned} \tag{15}
$$

According to Young's inequality [9], it can be given that

$$
2e_{Ti}^T(t)PNh(t) \le \|PN\|\,\|e_{Ti}(t)\|^2 + \|PN\|\,\|h(t)\|^2. \tag{16}
$$

Utilizing (15) and (16), it can be obtained that

$$
\begin{aligned}
&\dot{V}_t(t) \\
&\le \|PN\|\,\|e_{Ti}(t)\|^2 + \|PN\|\,\|h(t)\|^2 - e^T{}_{Ti}(t)Qe_{Ti}(t) \\
&\le \|PN\|\,\|h(t)\|^2 + (\|PN\| - \lambda_{\min}\{Q\})\,\|e_{Ti}(t)\|^2.
\end{aligned} \tag{17}
$$

Selection of suitable parameters χ_{i1} and χ_{i2} in (17) allows

$$
\begin{aligned}
\|e_{Ti}(t)\| &\le \sqrt{\frac{\|PN\|\,\|h(t)\|^2}{\lambda_{\min}\{Q\} - \|PN\|}} \\
&\le \sqrt{\frac{\|PN\|\,W^2}{\lambda_{\min}\{Q\} - \|PN\|}}.
\end{aligned} \tag{18}
$$

From (17)-(18), we can get $\dot{V}_t(t) \le 0$. Hence, the boundedness of all the signals in $V_t(t)$ are guaranteed, which means the position and velocity estimation error $e_{Ti}(t)$ is bounded. □

5. FORCE ESTIMATION ALGORITHM

In the BTSs, the acquisition of the interaction forces is quite necessary for precise tracking. Due to the complex work environment, force sensors have some problems such as high cost, low accuracy, difficult parameter-setting, and sensitive to noise. Therefore, the following force estimation algorithm is designed to estimate the human force

$$
\begin{cases}
\hat{\tau}_h = (\delta_m + \hat{\omega}_m)\,\alpha_m, \\
\alpha_m = r_m + \dot{r}_m - \beta_m, \\
\dot{\beta}_m = -M_m^{-1}(C_m\dot{q}_m + G_m) - M_m^{-1}\tau_m + M_m^{-1}\hat{\tau}_h, \\
\qquad + \dot{q}_m - \dot{q}_s - \ddot{q}_s + M_m^{-1}C_m\alpha_m,
\end{cases} \tag{19}
$$

where $\alpha_m \in R^n$ is an auxiliary variable, $\beta_m \in R^n$ is the state variable associated with the force estimation system, $\delta_m > 0$ is a constant, and the human force is bounded by ω_m, i.e., $\|\tau_h\| < \omega_m\,\|\alpha_m\|$. Besides, $\hat{\tau}_h$ is the estimation of τ_h and $\hat{\omega}_m$ is the estimation of ω_m. Here, r_m is the joint position error of the master which is defined as

$$
r_m = q_m - q_s. \tag{20}
$$

Differentiating (20) with respect to time gives us

$$
\dot{r}_m = \dot{q}_m - \dot{q}_s. \tag{21}
$$

Substituting (1) into the time derivative of (21), we can obtain

$$
\ddot{r}_m = M_m^{-1}(-\tau_m + \tau_h - C_m\dot{q}_m - G_m) - \ddot{q}_s. \tag{22}
$$

Considering that the bound of the human force is usually unknown in practice, an adaptive law based on the auxiliary variable β_m is designed to estimate the bound as

$$
\dot{\hat{\omega}}_m = b\alpha_m^T\alpha_m, \tag{23}
$$

where $b > 0$ is a constant.

Substituting (21) and (22) into the time derivative of α_m in (19), it can be obtained that

$$
\begin{aligned}
\dot{\alpha}_m &= \dot{r}_m + \ddot{r}_m - \dot{\beta}_m \\
&= \dot{q}_m - \dot{q}_s + M_m{}^{-1}(\tau_h - \tau_m - C_m\dot{q}_m - G_m) \\
&\quad - \ddot{q}_s - \dot{\beta}_m \\
&= M_m{}^{-1}(\tau_h - \hat{\tau}_h) - M_m{}^{-1}C_m\alpha_m.
\end{aligned} \tag{24}
$$

Next, the force estimation algorithm for the slave is designed to estimate the environment force as

$$
\begin{cases}
\hat{\tau}_e = (\delta_s + \hat{\omega}_s)\,\alpha_s, \\
\alpha_s = r_s + \dot{r}_s - \beta_s, \\
\dot{\beta}_s = M_s^{-1}(C_s\dot{q}_s + G_s) - M_s^{-1}\tau_s + M_s^{-1}\hat{\tau}_e, \\
\qquad - \dot{q}_s + \dot{q}_m + \ddot{q}_m + M_s^{-1}C_s\alpha_s,
\end{cases} \tag{25}
$$

where $\alpha_s \in R^n$ is an auxiliary variables, $\beta_s \in R^n$ is the state variables associated with the force estimation system, $\delta_s > 0$ is a constant, and the environment force is bounded by ω_s, i.e., $\|\tau_e\| < \omega_s\,\|\alpha_s\|$. Besides, $\hat{\omega}_s$ and $\hat{\tau}_e$ are the estimation of ω_s and τ_e, respectively. Since the desired position of the slave is the master position, the joint position error of the slave is also the position error of the master, i.e., $r_s = r_m = q_m - q_s$.

Substituting (2) into the time derivative of (21), we can obtain

$$
\ddot{r}_s = \ddot{q}_m - M_s^{-1}(\tau_s - \tau_e - C_s\dot{q}_s - G_s). \tag{26}
$$

Due to the complex and unknown environment in practice, an adaptive law based on the auxiliary variable β_s is designed to estimate the bound as

$$
\dot{\hat{\omega}}_s = b\alpha_s^T\alpha_s. \tag{27}
$$

Differentiating α_s in (25) and substituting (21) and (26) into it, we can get

$$
\begin{aligned}
\dot{\alpha}_s &= \dot{r}_s + \ddot{r}_s - \dot{\beta}_s \\
&= \dot{q}_m - \dot{q}_s + \ddot{q}_m - M_s{}^{-1}(\tau_s - \tau_e - C_s\dot{q}_s - G_s) - \dot{\beta}_s \\
&= M_s{}^{-1}(\tau_e - \hat{\tau}_e) - M_s{}^{-1}C_s\alpha_s.
\end{aligned} \tag{28}
$$

Theorem 2: For the BTSs (1) and (2) subjected to time-varying delays, using the force estimation algorithm (19) and (25) with the adaptive laws (23) and (27) the estimation error of the human force and the environment force can asymptotically converge to zero, i.e., $\lim_{t\to\infty}(\tau_h-\hat{\tau}_h)\to 0$, $\lim_{t\to\infty}(\tau_e-\hat{\tau}_e)\to 0$.

Proof: Define a Lyapunov function as

$$V_f=\frac{1}{2}\alpha_m^T M_m\alpha_m+\frac{1}{2b}(\omega_m-\hat{\omega}_m)^2+\frac{1}{2}\alpha_s^T M_s\alpha_s+\frac{1}{2b}(\omega_s-\hat{\omega}_s)^2. \tag{29}$$

Differentiating (29) with respect to time and substituting (23), (24), (27) and (28) into it gives us

$$\begin{aligned}\dot{V}_f&=\frac{1}{2}\alpha_m{}^T\dot{M}_m\alpha_m+\alpha_m{}^T M_m\dot{\alpha}_m-\frac{1}{b}(\omega_m-\hat{\omega}_m)\dot{\hat{\omega}}_m\\&\quad+\frac{1}{2}\alpha_s{}^T\dot{M}_s\alpha_s+\alpha_s{}^T M_s\dot{\alpha}_s-\frac{1}{b}(\omega_s-\hat{\omega}_s)\dot{\hat{\omega}}_s\\&=-\delta_m\alpha_m{}^T\alpha_m-\alpha_m{}^T(\omega_m\alpha_m-\tau_h)\\&\quad-\delta_s\alpha_s{}^T\alpha_s-\alpha_s{}^T(\omega_s\alpha_s-\tau_e).\end{aligned} \tag{30}$$

Then substituting $\|\tau_h\|<\omega_m\|\alpha_m\|$ and $\|\tau_e\|<\omega_s\|\alpha_s\|$ into (30) we can obtain

$$\begin{aligned}\dot{V}_f&<-\delta_m\|\alpha_m\|^2+\|\alpha_m\|\|\tau_h\|-\omega_m\|\alpha_m\|^2\\&\quad-\delta_s\|\alpha_s\|^2+\|\alpha_s\|\|\tau_e\|-\omega_s\|\alpha_s\|^2\\&<-\delta_m\|\alpha_m\|^2-\delta_s\|\alpha_s\|^2\\&<0.\end{aligned} \tag{31}$$

It is obvious from (31) that the estimation errors of the interaction forces can asymptotically converge to zero, i.e., $\lim_{t\to\infty}(\tau_h-\hat{\tau}_h)\to 0$ and $\lim_{t\to\infty}(\tau_e-\hat{\tau}_e)\to 0$.

6. DESIGN OF THE CONTROLLER

Using the obtained state information in Section 4 and the force estimation in Section 5, a P+D controller is designed in this section to simultaneously ensure the position tracking and force tracking. The controller of the master and slave are designed as

$$\tau_m=P_m(\hat{q}_s(t-d_s(t))-q_m(t))+B_m\dot{q}_m(t)+\hat{\tau}_h-G_m, \tag{32}$$

$$\tau_s=-P_s(q_s(t)-\hat{q}_m(t-d_m(t)))-B_s\dot{q}_s(t)+\hat{\tau}_e+G_s, \tag{33}$$

where P_m and P_s are positive definite position gains of the master and slave, B_m and B_s are the velocity gains such that $B_m-(D_m+D_s)I$ and $B_s-(D_m+D_s)I$ are positive definite matrices.

The master controller τ_m can be viewed as four parts. The first part $P_m(\hat{q}_s(t-d_s(t))-q_m(t))$ is for position tracking of the master and slave. The second part $B_m\dot{q}_m(t)$ is for velocity compensation. The third part $\hat{\tau}_h$ is for the human force compensation in the dynamics. The fourth part $-G_m$ is for the gravity compensation. The slave controller τ_s has the similar structure to the master controller.

Theorem 3: For the BTSs (1) and (2) subjected to time-varying delays, the P+D controllers (32) and (33) based on the TDSO (6) and (7) and the force estimation algorithm (19) and (25) can ensure that the position tracking error asymptotically converges to zero, i.e., $\lim_{t\to\infty}(q_m(t)-q_s(t-d_s(t)))\to 0$. Meanwhile, the human force and environment force can achieve force tracking, i.e., $\lim_{t\to\infty}(\tau_h+\tau_e)\to 0$.

Proof: Define a Lyapunov function $V_c(t)$ as

$$V_c(t)=V_1(t)+V_2(t)+V_3(t), \tag{34}$$

where

$$\begin{aligned}V_1(t)&=\frac{1}{2}\dot{q}_m^T(t)M_m\dot{q}_m(t)+\frac{P_m}{P_S}\dot{q}_S^T(t)M_s\dot{q}_s(t),\\V_2(t)&=\frac{P_m}{2}r_m(t)^T r_m(t),\\V_3(t)&=\int_{-D_m}^{0}\int_{t+\gamma}^{t}\dot{q}_m^T(\eta)\dot{q}_m(\eta)\,d\eta\,d\gamma\\&\quad+\int_{-D_s}^{0}\int_{t+\gamma}^{t}\dot{q}_s^T(\eta)\dot{q}_s(\eta)\,d\eta\,d\gamma.\end{aligned} \tag{35}$$

According to Property 1, the time derivative of $V_1(t)$ can be rewritten as

$$\begin{aligned}\dot{V}_1(t)&=P_m\left(-\frac{1}{P_m}\dot{q}_m^T(t)G_m+\dot{q}_m^T(t)\tau_h-\dot{q}_m^T(t)\tau_m(t)\right)\\&\quad-P_m\left(-\frac{1}{P_S}\left(\dot{q}_s^T(t)G_s+\dot{q}_s^T(t)\tau_s(t)-\dot{q}_s^T(t)\tau_e\right)\right).\end{aligned} \tag{36}$$

Now define the position tracking errors of the master and the slave as $e_m=q_m(t)-q_s(t-d_s(t))$ and $e_s=q_s(t)-q_m(t-d_m(t))$, respectively. Differentiating $V_2(t)$ and introducing $d_m(t)$ and $d_s(t)$ into it, we can get

$$\begin{aligned}\dot{V}_2(t)&=P_m\dot{q}_m^T(t)r_m(t)-P_m\dot{q}_s^T(t)r_m(t)\\&=P_m\dot{q}_m^T(t)(q_s(t-d_s(t))-q_s(t))+P_m\dot{q}_m^T(t)e_m\\&\quad+P_m\dot{q}_s^T(t)e_s+P_m\dot{q}_s^T(t)(q_m(t-d_m(t))\\&\quad-q_m(t)).\end{aligned} \tag{37}$$

Since

$$\begin{aligned}&\dot{q}_m^T(t)(q_s(t-d_s(t))-q_s(t))\\&\quad+\dot{q}_s^T(t)(q_m(t-d_m(t))-q_m(t))\\&=-\dot{q}_m^T(t)\int_{t-d_s(t)}^{t}\dot{q}_s(\mu)\,d\mu-\dot{q}_s^T(t)\int_{t-d_m(t)}^{t}\dot{q}_m(\vartheta)\,d\vartheta.\end{aligned} \tag{38}$$

Now substituting (38) into (37), $\dot{V}_2(t)$ can be simplified to

$$\dot{V}_2(t)=P_m\dot{q}_m^T(t)e_m-P_m\dot{q}_m^T(t)\int_{t-d_s(t)}^{t}\dot{q}_s(\mu)\,d\mu$$

$$+P_m\dot{q}_s^T(t)e_s-P_m\dot{q}_s^T(t)\int_{t-d_m(t)}^{t}\dot{q}_m(\vartheta)\,d\vartheta. \tag{39}$$

The time derivative of $V_3(t)$ can be given as

$$\begin{aligned}\dot{V}_3(t)=&D_m\dot{q}_m^T(t)\dot{q}_m(t)-\int_{t-D_m}^{t}\dot{q}_m^T(\vartheta)\dot{q}_m(\vartheta)\,d\vartheta\\&+D_s\dot{q}_s^T(t)\dot{q}_s(t)-\int_{t-D_s}^{t}\dot{q}_s^T(\mu)\dot{q}_s(\mu)\,d\mu\\\le&D_m\dot{q}_m^T(t)\dot{q}_m(t)-\int_{t-d_m(t)}^{t}\dot{q}_m^T(\vartheta)\dot{q}_m(\vartheta)\,d\vartheta\\&+D_s\dot{q}_s^T(t)\dot{q}_s(t)-\int_{t-d_s(t)}^{t}\dot{q}_s^T(\mu)\dot{q}_s(\mu)\,d\mu.\end{aligned} \tag{40}$$

Using Lemma 1 in [23] we can obtain

$$\begin{aligned}&-\dot{q}_m^T(t)\int_{t-d_s(t)}^{t}\dot{q}_s(\mu)\,d\mu-\int_{t-d_s(t)}^{t}\dot{q}_s^T(\mu)\dot{q}_s(\mu)\,d\mu\\&\le D_s\dot{q}_m^T(t)\dot{q}_m(t),\\&-\dot{q}_s^T(t)\int_{t-d_m(t)}^{t}\dot{q}_m(\vartheta)\,d\vartheta-\int_{t-d_m(t)}^{t}\dot{q}_m^T(\vartheta)\dot{q}_m(\vartheta)\,d\vartheta\\&\le D_m\dot{q}_s^T(t)\dot{q}_s(t).\end{aligned} \tag{41}$$

Substituting (36), (39), (40), and (41) into the time derivative of (34), the time derivative of (34) can be simplified as

$$\begin{aligned}\dot{V}_c(t)\le&\dot{q}_m^T(t)\left(P_me_m-G_m-\tau_m(t)+\tau_h\right)\\&+\frac{\dot{q}_s^T(t)}{P_s}\left(-P_mG_s+P_m\tau_s(t)-P_m\tau_e\right)\\&+\dot{q}_s^T(t)P_me_s+\dot{q}_m^T(t)\left(D_m+D_s\right)\dot{q}_m(t)\\&+\dot{q}_s^T(t)\left(D_m+D_s\right)\dot{q}_s(t).\end{aligned} \tag{42}$$

Substituting the controller (32) and (33) into (42), $\dot{V}_c(t)$ can be simplified to

$$\begin{aligned}\dot{V}_c(t)\le&-\dot{q}_m^T(t)\left(B_m-(D_m+D_s)I\right)\dot{q}_m(t)\\&-\dot{q}_s^T(t)\left(B_s-(D_m+D_s)I\right)\dot{q}_s(t)\\\le&\,0.\end{aligned} \tag{43}$$

Equation (43) indicates that all the signals in $V_c(t)$ are bounded for any bounded $\dot{d}_i$. Therefore, $q_m(t)-q_s(t)$ is bounded.

Since (43) indicates that all the signals in $V_c(t)$ are bounded, we have $q_s(t)\in L_\infty$ and $\dot{q}_s(t)\in L_\infty$. Moreover, due to $e_m=q_m(t)-q_s(t)+\int_{t-d_s(t)}^{t}\dot{q}_s(t)$, we can obtain $e_m\in L_\infty$. According to (33), (2) can be rewritten as

$$\begin{aligned}\ddot{q}_s(t)=&M_s^{-1}\left(-P_s\left(q_m(t)-\hat{q}_s\left(t-d_s(t)\right)\right)-C_s\dot{q}_s\right.\\&\left.-B_s\dot{q}_s\right).\end{aligned} \tag{44}$$

Then using Properties 2 and 3, we can obtain $\ddot{q}_s(t)\in L_\infty$. As $\dot{q}_s(t)\in L_\infty$ and $\ddot{q}_s(t)\in L_\infty$ have already been obtained, utilizing Barbalat's lemma [24] we can get $\lim_{t\to\infty}\dot{q}_s(t)\to 0$.

Differentiating (44) gives us

$$\begin{aligned}&\dddot{q}_s(t)\\&=M_s^{-1}\frac{d(-C_s\dot{q}_s-B_s\dot{q}_s-P_s(q_m(t)-\hat{q}_s(t-d_s(t))))}{d(t)}\\&\quad+\dot{M}_s^{-1}(-C_s\dot{q}_s-B_s\dot{q}_s-P_s(q_m(t)-\hat{q}_s(t-d_s(t)))).\end{aligned} \tag{45}$$

Using Property 1, we have

$$\dot{M}_s^{-1}=-M_s^{-1}\left(C_s+C_s^T\right)M_s. \tag{46}$$

Equation (46) indicates that $\dot{M}_s^{-1}$ is bounded. Then e_m, $\dot{q}_s(t)$, $\ddot{q}_s(t)$ and $\dot{d}_s(t)$ are bounded. Consequently, the derivative of C_s is bounded. Thus, according to (45), $\dddot{q}_i(t)\in L_\infty$ can be obtained. Since we have already had $\lim_{t\to\infty}\dot{q}_s(t)\to 0$ and $\dddot{q}_s(t)\in L_\infty$, using Barbalat's lemma we can obtain $\lim_{t\to\infty}\ddot{q}_s(t)\to 0$.

Substituting $\lim_{t\to\infty}\dot{q}_s(t)\to 0$ and $\lim_{t\to\infty}\ddot{q}_s(t)\to 0$ into (2) and (33), we have $\lim_{t\to\infty}\left(q_s(t)-q_m\left(t-d_m(t)\right)\right)\to 0$. Similarly, $\lim_{t\to\infty}\left(q_m(t)-q_s\left(t-d_s(t)\right)\right)\to 0$ can be obtained. Consequently, the position tracking errors e_m and e_s can converge to zero.

Next, we will further analyze the force tracking performance. When the slave contacts with the environment, it is reasonable to assume that [20]

$$\begin{aligned}&\dot{\tau}_h\approx 0,\ \dot{\tau}_e\approx 0,\\&\dot{q}_i\approx 0,\\&\ddot{q}_i\approx 0,\\&q_i(t)=q_i\left(t-d_i(t)\right).\end{aligned} \tag{47}$$

Substituting the controller (32) and (33) into the BTSs (1) and (2), the closed-loop system is obtained as

$$\begin{aligned}&\tau_h-\hat{\tau}_h=P_m\left(q_m-q_s\right),\\&\tau_e-\hat{\tau}_e=P_s\left(q_m-q_s\right).\end{aligned} \tag{48}$$

As the force estimation algorithm can obtain the estimations of the interaction forces, the estimation values can approximate their true values, i.e., $\hat{\tau}_h=\theta_h\tau_h$ and $\hat{\tau}_e=\theta_e\tau_e$, where $\lim_{t\to\infty}\theta_h\to 1$ and $\lim_{t\to\infty}\theta_e\to 1$. Then it is given that

$$\begin{aligned}&\tau_h=\frac{P_m\left(q_m-q_s\right)}{\left(1-\theta_h\right)},\\&\tau_e=\frac{P_s\left(q_m-q_s\right)}{\left(1-\theta_e\right)}.\end{aligned} \tag{49}$$

From (49), it follows that there exist suitable P_m, P_s, θ_h, and θ_e such that $\lim_{t\to\infty}(\tau_h+\tau_e)\to 0$, thus enabling the force tracking performance. □

Remark 1: In the proof of Theorem 3, it can be seen that $q_m(t)-q_s(t)$ is bounded without requiring $\dot{d}_i$ to be bounded. Moreover, the position tracking error $q_m(t)-q_s\left(t-d_s(t)\right)$ converges to zero only requiring that $\dot{d}_i$ is bounded, while it does not require that the bound of $\dot{d}_i$ is less than one.

7. SIMULATIONS

In the simulations, the master and slave manipulators in the BTSs are considered to be 2-DOF robots with revolute joints as

$$M_i(q_i) = \begin{bmatrix} p_1 + p_2 + 2p_3 \cos q_{i2} & p_2 + p_3 \cos q_{i2} \\ p_2 + p_3 \cos q_{i2} & p_2 \end{bmatrix}, \tag{50}$$

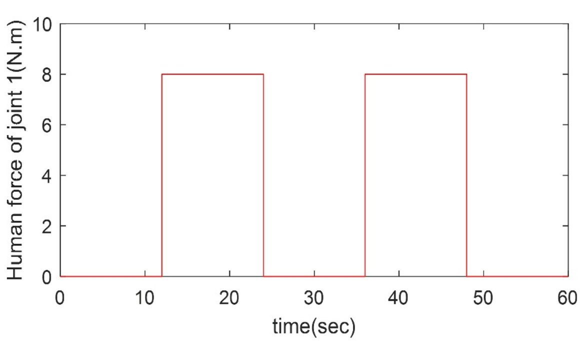
$$C_i(q_i, \dot{q}_i) = \begin{bmatrix} -p_3 \dot{q}_{i2} \sin q_{i2} & -p_3(\dot{q}_{i1} + \dot{q}_{i2}) \sin q_{i2} \\ p_3 \dot{q}_{i1} \sin q_{i2} & 0 \end{bmatrix}, \tag{51}$$

$$G_i(q_i) = \begin{bmatrix} p_4 g \cos q_{i1} + p_5 g \cos(q_{i1} + q_{i2}) \\ p_5 g \cos(q_{i1} + q_{i2}) \end{bmatrix}, \tag{52}$$

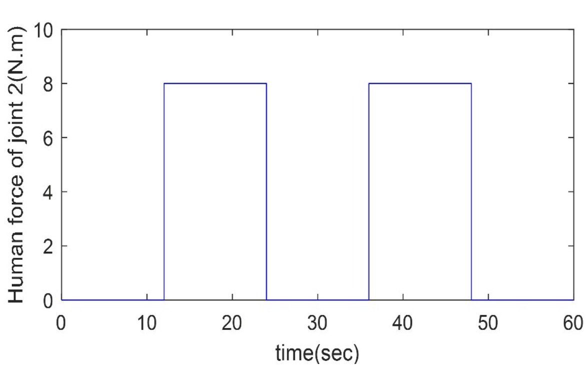
where $i \in \{m, s\}$ denotes the master and slave, respectively, and $q_i = \begin{bmatrix} q_{i1} \\ q_{i2} \end{bmatrix}$ is the joint position. The initial positions of the two joints are $q_{m0} = \begin{bmatrix} 0.1 \\ 0.05 \end{bmatrix}$ and $q_{s0} = \begin{bmatrix} -0.1 \\ -0.1 \end{bmatrix}$, respectively. Besides, $[p_1, p_2, p_3, p_4, p_5]^T = [2.90, 0.76, 0.87, 3.04, 0.87]^T$ and $g = 9.8$ m/s^2. The forward communication delay $d_m(t)$ and backward communication delay $d_s(t)$ are random signals to reflect the time-varying nature of the delays. The human force τ_h is shown in Fig. 2, and the environment force τ_e is modeled by a second-order system as$\tau_e = M_e \ddot{q}_s + B_e \dot{q}_s + K_e q_s$, where $M_e = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.1 \end{bmatrix}$, $B_e = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, and $K_e = \begin{bmatrix} 330 & 0 \\ 0 & 1000 \end{bmatrix}$ denote the mass, damping, and stiffness of the environment, respectively. The gain matrices of the controller in the simulations are given as $P_m = \begin{bmatrix} 1 & 0 \\ 0 & 10 \end{bmatrix}$, $P_s = \begin{bmatrix} 50 & 0 \\ 0 & 150 \end{bmatrix}$, $B_m = \begin{bmatrix} 15 & 0 \\ 0 & 20 \end{bmatrix}$, $B_s = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix}$. Other parameters are given as $\sigma_m = 100$, $\sigma_s = 150$.

In the simulations, the proposed control method is compared with the control method in [20]. When the system is subjected to time-varying delays, Fig. 3 shows that the position tracking performance of [20] is not satisfactory. When the human force is applied (12 sec-24 sec and 36 sec-48 sec), the slave cannot well track the position of the master and cannot respond smoothly to the position change of the master. Comparatively, as shown in Fig. 4, when utilizing the proposed control method, the salve can fast track the master when the human force is applied. Moreover, the response of the slave is smoother and the position tracking error is smaller.

Figs. 5 and 6 show the positions affected by time-varying delays and their estimations by TDSO. It can be seen that the TDSO can well estimate the delayed positions of the master and slave. Notice that there is no TDSO in [20] and thus it is not shown in the figures.

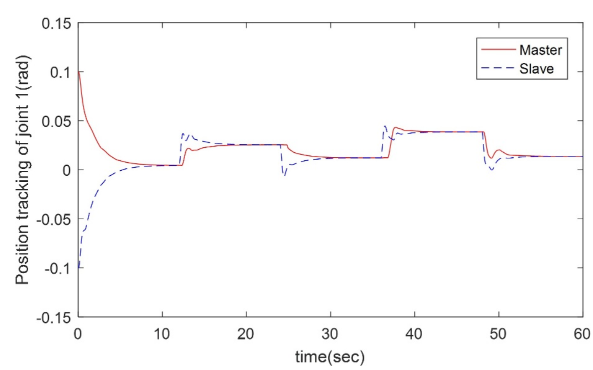


(a)

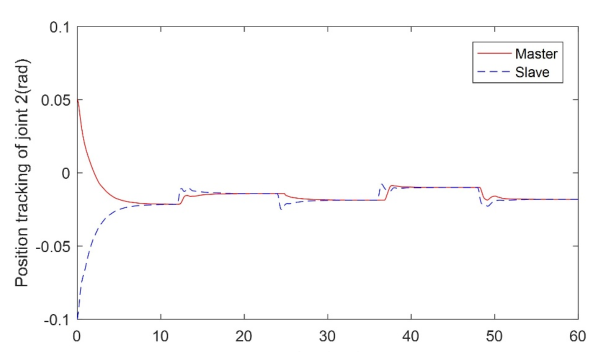


(b)

Fig. 2. Human force, (a) joint 1 and (b) joint 2.



(a)



(b)

Fig. 3. Position tracking (the method in [20]), (a) joint 1 and (b) joint 2.

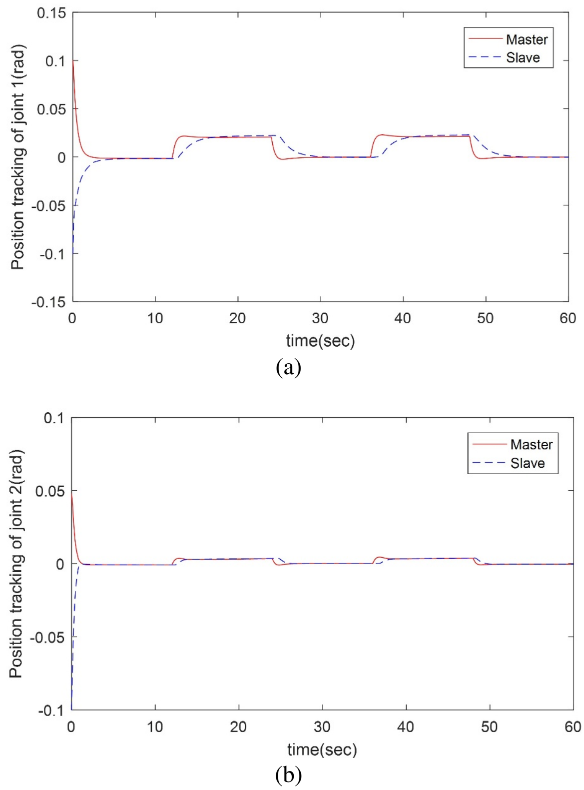


Fig. 4. Position tracking (the proposed method), (a) joint 1 and (b) joint 2.

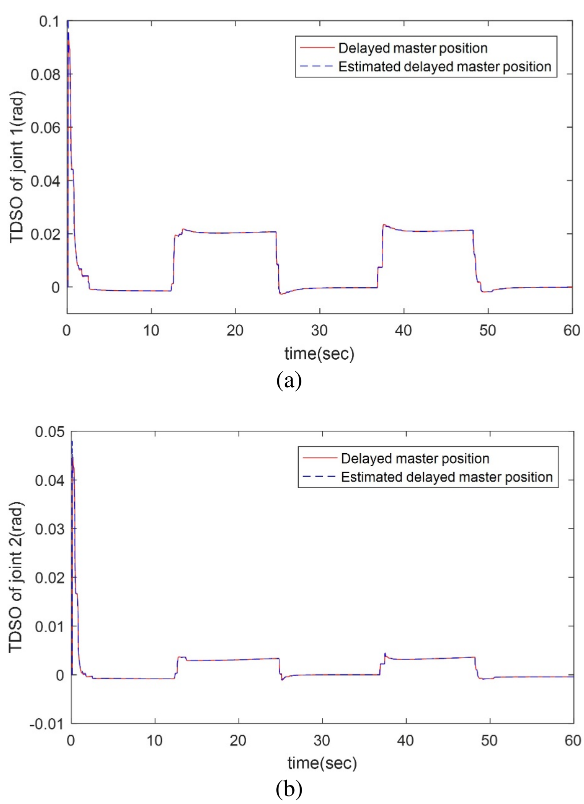


Fig. 5. Estimation of delayed master position (the proposed method), (a) joint 1 and (b) joint 2.

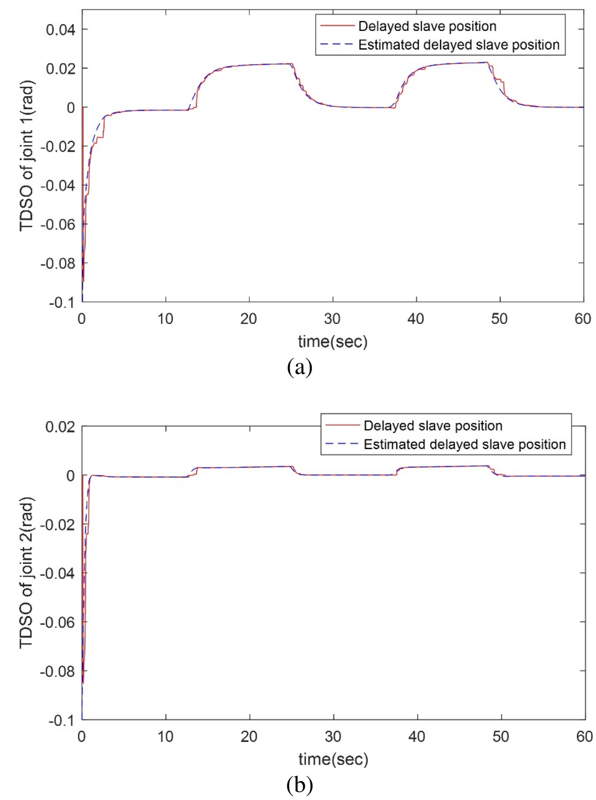


Fig. 6. Estimation of delayed slave position (the proposed method), (a) joint 1 and (b) joint 2.

The force estimation of [20] is shown in Figs. 7 and 8, which indicates that the estimations of the human force and the environment force have chattering and become significantly worse when the human force changes abruptly (12 sec, 24 sec, 36 sec, 24 sec). The proposed force estimation algorithm is shown in Figs. 9 and 10. When applying the human force, the estimations of the interaction forces are smoother without significant chattering, and the estimation errors are smaller, which indicates that the interaction forces can be effectively obtained.

Figs. 11 and 12 show the force tracking of [20] and the proposed control method, respectively. In Fig. 11, the force tracking between the human and the environment has significant chattering and is not accurate, while in Fig. 12, the force tracking is more accurate without significant chattering when the human force is applied. Therefore, the slave can better reflect the environment force to the master with the proposed control method.

8. EXPERIMENTS

As shown in Fig. 13, the experimental setup consists of two Phantom Omni force feedback robots including the Phantom Omni #1 robot (master) and the Phantom Omni #2 robot (slave). The master is connected to the computer while the master is connected to the slave by a 1394 fireware.

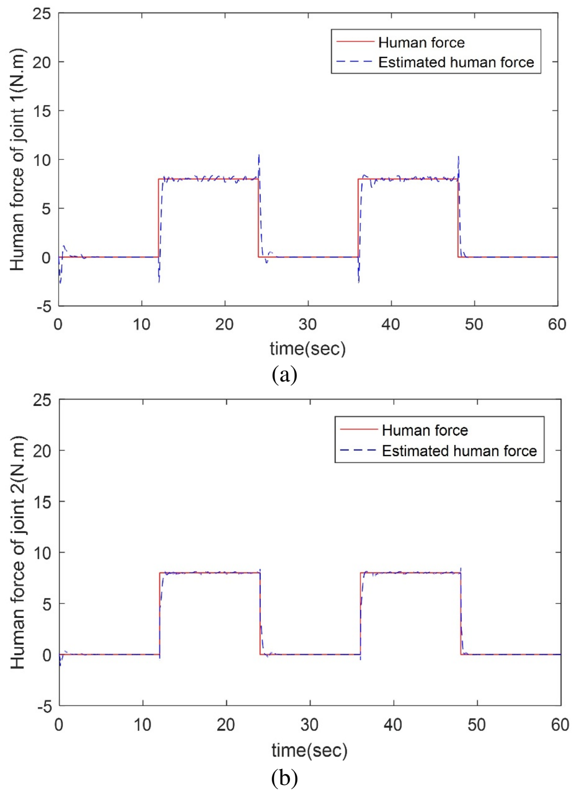


Fig. 7. Human force estimation (the method in [20]), (a) joint 1 and (b) joint 2.

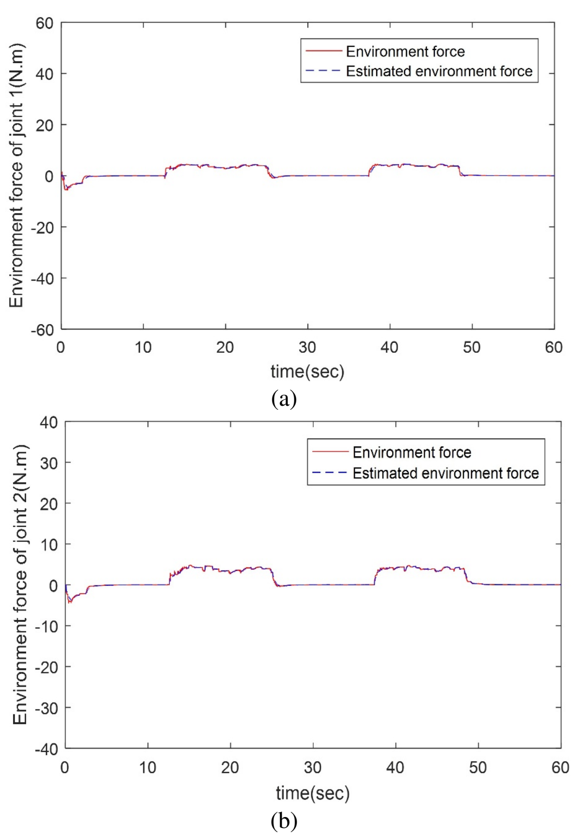


Fig. 8. Environment force estimation (the method in [20]), (a) joint 1 and (b) joint 2.

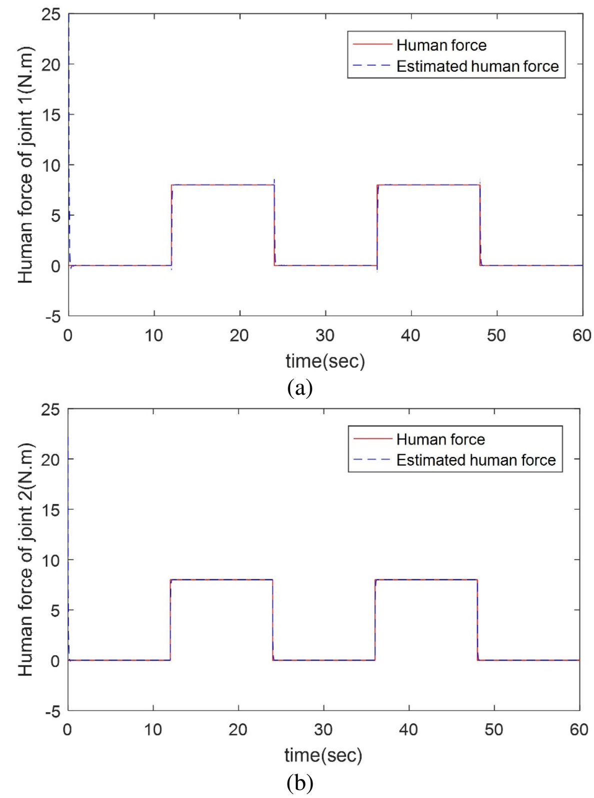


Fig. 9. Human force estimation (the proposed method), (a) joint 1 and (b) joint 2.

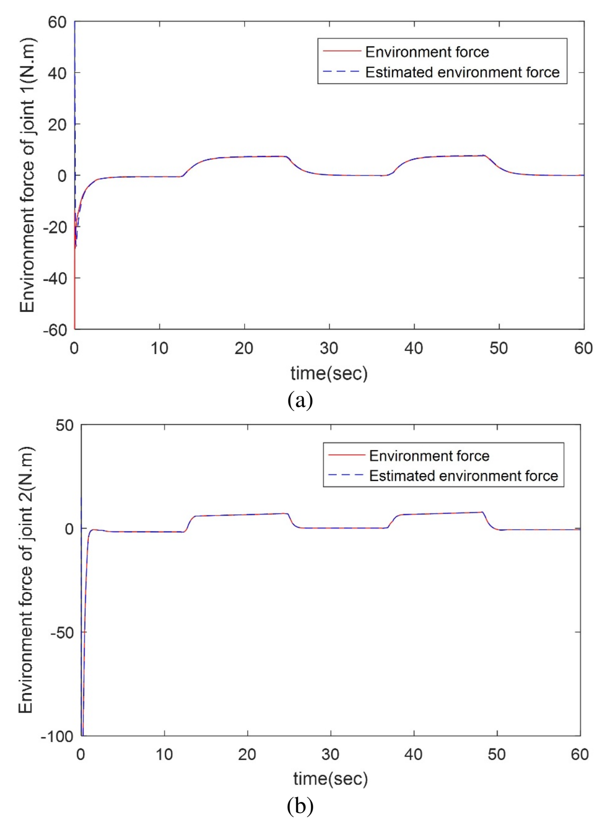
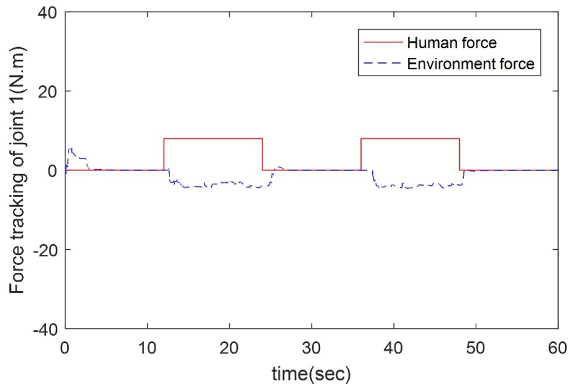
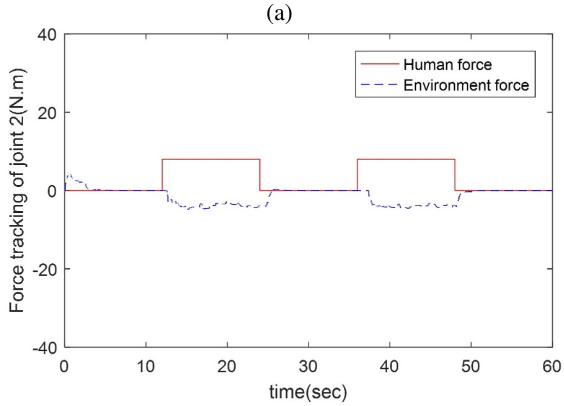


Fig. 10. Environment force estimation (the proposed method), (a) joint 1 and (b) joint 2.

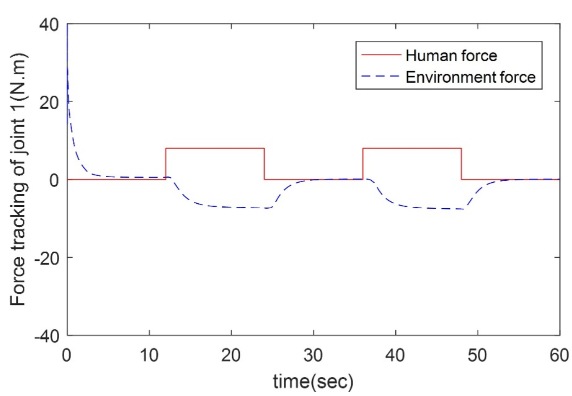


(a)

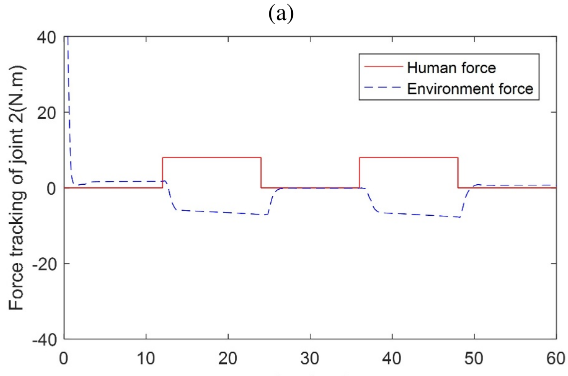


(b)

Fig. 11. Force tracking (the method in [20]), (a) joint 1 and (b) joint 2.



(a)



(b)

Fig. 12. Force tracking (the proposed method), (a) joint 1 and (b) joint 2.

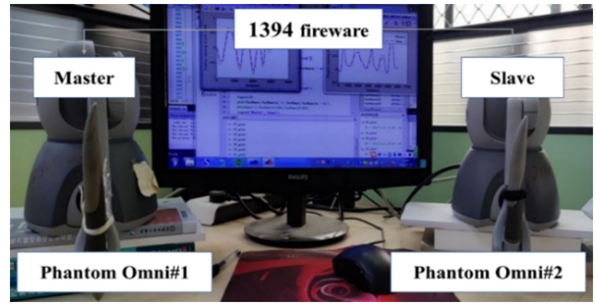
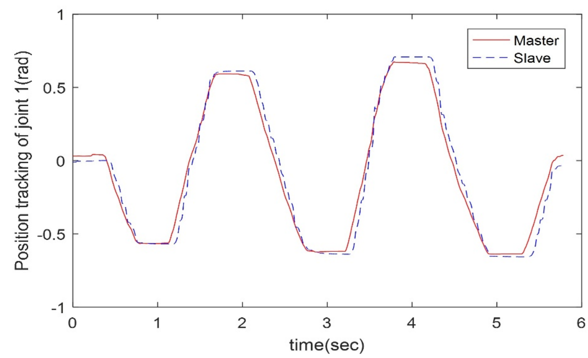
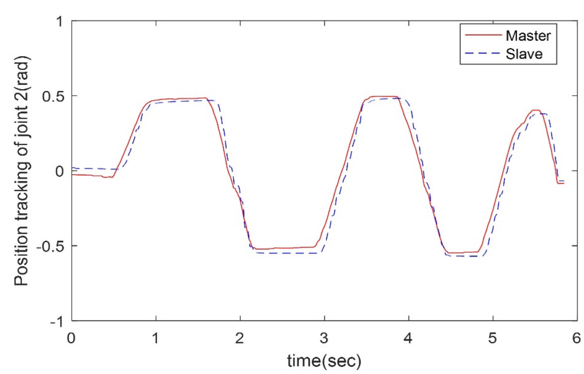


Fig. 13. Master-slave robot teleoperation experiment setup.



(a)



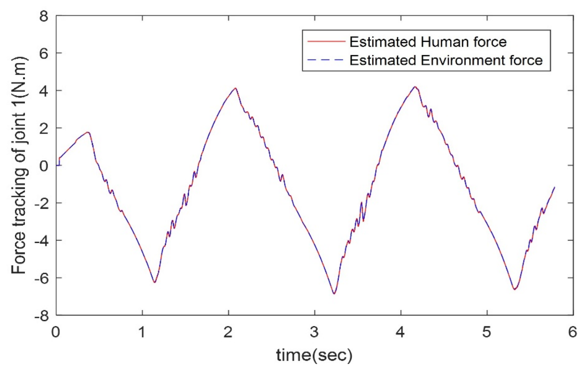
(b)

Fig. 14. Position tracking, (a) joint 1 and (b) joint 2.

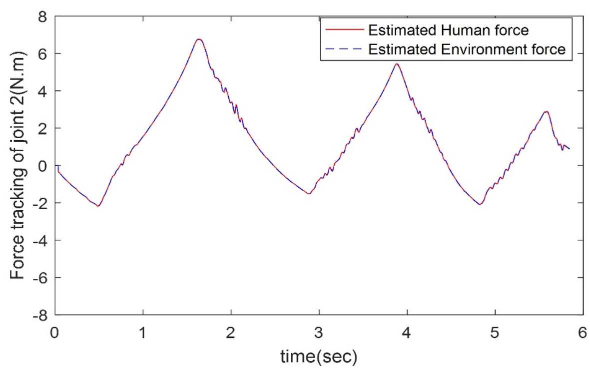
In the experiments, $d_m(t)$ and $d_s(t)$ are random variables between 1 and 250 ms. The initial positions of the two robots are $q_{m0} = \begin{bmatrix} 0.032 \\ -0.028 \end{bmatrix}$ and $q_{s0} = \begin{bmatrix} -0.004 \\ 0.015 \end{bmatrix}$. The gain matrices of the controller in the experiment are $P_m = P_s = \begin{bmatrix} 3 & 0 \\ 0 & 5 \end{bmatrix}$, $B_m = B_s = \begin{bmatrix} 2 & 0 \\ 0 & 2.5 \end{bmatrix}$. Besides, $\sigma_m = \sigma_s = 0.1$.

The position tracking of the proposed control method is shown in Fig. 14. When the system is subjected to time-varying delays, it can be seen that the slave can still quickly respond to the master and the position tracking error is small.

The force tracking of the proposed control method is



(a)



(b)

Fig. 15. Force tracking, (a) joint 1 and (b) joint 2.

shown in Fig. 15, which indicates that the estimated human force can quickly and accurately track the estimated environment force. Hence, the force tracking performance is achieved. This also indicates that the operator can accurately feel the interaction forces between the slave and the environment.

Remark 2: In order to avoid the use of force sensors, force sensors were not used in the experiments to measure the interaction forces. Instead, as shown in Fig. 15, the force estimation algorithm is adopted to obtain the estimations of the human force and the environment force. Furthermore, from Theorem 2 it is known that the estimation error of the interaction forces can converge to zero. Therefore, the estimated force tracking performance can reflect the realistic force tracking performance in the experiments.

9. CONCLUSION

For bilateral teleoperation systems with time-varying delays, a position and force tracking control based on force estimation is proposed. The proposed control method can simultaneously improve the position and force tracking performance. Meanwhile, it can avoid the measurement of interaction forces by sensors and does not need to constrain the bound of the derivative of the time-varying delays to be less than one.

How to extend the proposed approach to multilateral teleoperation systems (multi-master/single-slave teleoperation systems, single-master/multi-slave teleoperation systems, and multi-master/multi-slave teleoperation systems) to achieve more flexible teleoperation tasks will be our future work.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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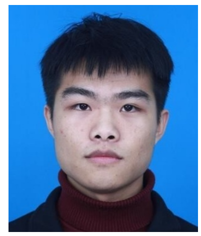

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