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RBFNN-Based Adaptive Sliding Mode Control Design for Nonlinear Bilateral Teleoperation System Under Time-Varying Delays

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ABSTRACT The bilateral teleoperation technique has drawn much attention with its attractive superiority to implement the tasks in hazardous environments. Transmission delays and uncertainties are the two main challenges in the nonlinear bilateral teleoperation system to guarantee stability and achieve good transparency performance (including position tracking and force feedback) simultaneously. In this paper, a radial basis function neural network (RBFNN)-based adaptive sliding mode control design is developed for the nonlinear bilateral teleoperation system with transmission delays and uncertainties. For details, the reference trajectory producer is designed in both the master and slave sides to produce the passive reference trajectories for the tracking of master/slave manipulators. The RBFNN-based adaptive sliding mode controller is designed separately for the master and slave to achieve the good tracking performance under system uncertainties. To mitigate the negative effect of transmission delays on the system's stability, a projection mapping by saturation function is applied in the master side to guarantee the boundedness of the delayed environmental torque. Thus, the global stability and the good transparency performance with both position tracking and force feedback can be simultaneously achieved for our proposed method. The comparative experiment is carried out, and the results show the significant performance improvement with our proposed control design.

INDEX TERMS Bilateral teleoperation, adaptive sliding mode control, neural network, transmission delays, uncertainties.

I. INTRODUCTION

With the advancement of automation and robotics [1]–[9], the bilateral teleoperation technique, which is an efficient and secure approach to implement the remote tasks in hazardous or extreme environments with force feedback, has been applied in numerous fields such as the undersea exploration, medical surgery, and so on [10]–[12]. A typical bilateral teleoperation system consists of the human operator, master, communication channel, slave and the environment [13], as shown in Fig.1, where the master is operated by human operator in a safe place and send reference command signals to the slave through communication channel, and the slave tracks the received signals to perform the operation in the environments and transmits the environment information back to the master [14].

Stability and transparency are the two non-negligible performances in the bilateral teleoperation system, which have been investigated for several decades [15], [16]. The stability of a bilateral teleoperation system must be guaranteed in case of the transmission delays between master and slave subsystem with nonlinearities and uncertainties, while the transparency with both position tracking and force feedback requires the slave to imitate the behavior of the master manipulator and the remote environment to be perceived by the human operator [17]. However, these two performances are affected by the great nonlinearities and uncertainties of the master/slave subsystems with the transmission delays [18].

The transmission delays, which are the inherent property in the communication channel to deteriorate system's stability, have been studied for many years [19]. The passivity-based

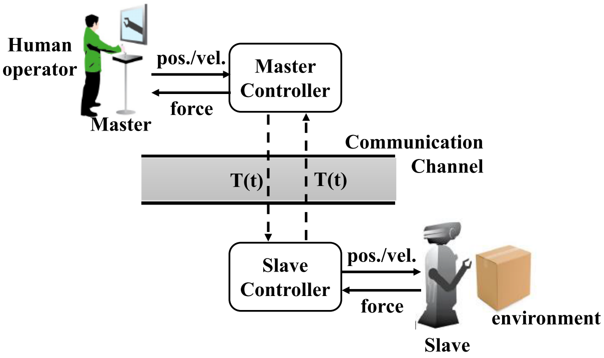

FIGURE 1. Architecture of bilateral teleoperation system.

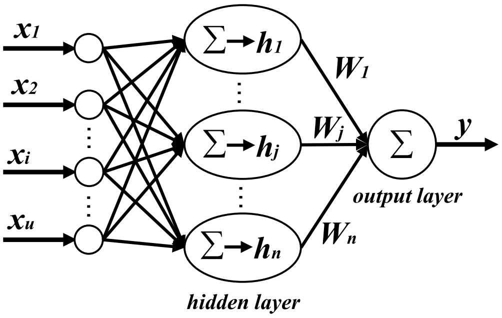

FIGURE 2. The architecture of RBFNN.

control scheme [20]–[24] is developed to maintain the passivity of the bilateral teleoperation system with transmission delays, which guarantees the system's closed-loop stability. For example, the scattering operator [20], [21] is introduced to judge the passivity of the bilateral teleoperation system with the architecture of 2-port network. The time-domain passivity architecture [22] is developed to guarantee the stability by the design of observer to maintain the energy conservation of the bilateral teleoperation system. The wave-variable transform [23], [24] is introduced to convert the power signals in the communication channel to the wave variables, which guarantees the system's stability. However, the obvious drawback of passivity-based control scheme is that the system may exist some performance deficiencies (e.g., wave reflection), which will largely decrease the transparency performance of teleoperation system [16]. The four-channel architecture, which relies on the control parameter fit between the master and slave subsystems, is an useful approach to obtain good transparency performance [25]. Therefore, the idea of combining the passivity-based control scheme with four-channel architecture is developed to achieve simultaneous stability and good transparency performance [15], [26].

The great nonlinearities and uncertainties of the master/slave subsystems with multi-degree-of-freedom are another main challenge for bilateral teleoperation system [27]. The prescribed performance control design with barrier Lyapunov function is introduced to provide the good transient-state performance with additional synchronization constraints [28]–[30]. A switching terminal sliding mode surface is introduced in [31], where the fuzzy logic system is used to approximate the modeling uncertainties for master/slave subsystems. The neural networks are applied with the design of new error transformed variables in [32] to let the tracking errors quickly converge to zero. The neural-network-based passivity control scheme with the type-2 fuzzy model of master/slave subsystems is designed in [33] and [34], where the nonlinear teleoperation system is divided into a group of linear models for the implementation of robust control algorithms via mature linear theories.

Though many control strategies have been tried to handle these two performances of the bilateral teleoperation system, to achieve simultaneous stability and good transparency performance is still challenging [35]. Therefore, focus on these two performances, an RBFNN(*Radial Basis Function Neural Network*)-based adaptive sliding mode control (ASMC) design is developed in this paper. The reference trajectory producer is designed in both the master and slave sides to produce the passive reference trajectories for the tracking of master/slave manipulators, and the RBFNN-based adaptive sliding mode controller is designed separately for the master and slave to achieve the good tracking performance under system uncertainties, where the enrollment of sliding mode control scheme has the advantage of fast convergence. A projection mapping by saturation function is applied in the master side to guarantee the boundedness of the delayed environmental torque, which mitigates the negative effect of transmission delays on the system's stability. Thus, the global stability and good transparency performance including the position tracking and force feedback can be simultaneously achieved for our proposed method. The comparative experiment is implemented and the results verify the significant performance improvement with our proposed control design.

The rest of this paper is organized as follows. Section II introduces the definition of RBFNN. Section III introduces the modeling of nonlinear bilateral teleoperation system. Section IV presents an RBFNN-based adaptive sliding mode control design in bilateral teleoperation system with the detailed stability and transparency analyses. Section V implements the experiment, and the comparative results verify the superiorities of proposed design. Section VI summarizes the whole paper.

II. THE DEFINITION OF RBFNN

With the characteristic of universal approximation, the RBFNN(*Radial Basis Function Neural Network*) algorithm has been widely used in the control design of the model-uncertain systems [36]. The definition is introduced in details as follows.

Definition 1: The RBFNN is a forward neural network consisting of 3 layers with u inputs, n hidden nodes and 1 output, as shown in Fig.2.

Define the input of RBFNN as:

$$x = [x_1, \ldots, x_i, \ldots, x_u]^T \tag{1}$$

Then the Gaussian function is obtained as:

$$h_j(x) = \exp\left(\frac{\left\|x-c_j\right\|^2}{2b_j^2}\right) \tag{2}$$

$$h(x) = [h_j(x)]^T \tag{3}$$

where $||\bullet||$ is the Euclidean norm of $\bullet$, $j = 1, \ldots, n$, $c_j = [c_{j1}, \ldots, c_{ji}, \ldots, c_{ju}]^T$, $C = [c_1, \ldots, c_j, \ldots, c_n]$.

Therefore, the output of RBFNN is derived as:

$$y = \sum_{j=1}^{n} W_j h_j(x) + \varepsilon = W^T h(x) + \varepsilon \tag{4}$$

where $W = [W_1, \ldots, W_j, \ldots, W_n]^T$, ε is the estimation error, and $\varepsilon \leq \bar{\varepsilon}$. ■

III. BILATERAL TELEOPERATION SYSTEM MODELING

Consider the following nonlinear master/slave teleoperation manipulators:

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) + D_m = \tau_m + \tau_h \tag{5}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) + D_s = \tau_s + \tau_e \tag{6}$$

where $q_m, \dot{q}_m, \ddot{q}_m$ and $q_s, \dot{q}_s, \ddot{q}_s$ are the displacement, velocity and acceleration for master/slave manipulators. M_m, M_s are the mass inertia matrixes, C_m, C_s are the coriolis/centrifugal matrixes. G_m, G_s are the gravitational matrixes. D_m, D_s are the disturbance and modeling errors. τ_m, τ_s are the control inputs. τ_h is the human operating torque, and τ_e is the environmental torque.

Some properties and assumptions of (5) and (6) are as follows:

Property 1: $\dot{M}_m - 2C_m, \dot{M}_s - 2C_s$ are skew-symmetric.

Property 2: Part of (5) and (6) can be written in the form of RBFNN as:

$$\begin{aligned} M_m(q_m)\ddot{q}_{md} + C_m(q_m, \dot{q}_m)\dot{q}_{md} + G_m(q_m) \\ = W_m^T h(q_m, \dot{q}_m, \dot{q}_{md}, \ddot{q}_{md}) \end{aligned} \tag{7}$$

$$\begin{aligned} M_s(q_s)\ddot{q}_{sd} + C_s(q_s, \dot{q}_s)\dot{q}_{sd} + G_s(q_s) \\ = W_s^T h(q_s, \dot{q}_s, \dot{q}_{sd}, \ddot{q}_{sd}) \end{aligned} \tag{8}$$

Assumption 1: The norm of D_m and D_s are bounded with the upper bound as:

$$\|D_m\| \leq \bar{d}_m, \quad \|D_s\| \leq \bar{d}_s \tag{9}$$

IV. CONTROL DESIGN FOR NONLINEAR BILATERAL TELEOPERATION SYSTEM

A. CONTROL SCHEME

The proposed control scheme is shown in Fig. 3, where the time-varying transmission delays $T(t)$ exist in the communication channel. A reference trajectory producer is designed in the slave side to derive the reference trajectories $q_{sd}, \dot{q}_{sd}, \ddot{q}_{sd}$ with the only delayed master position signal $q_m(t)$, and a projection mapping by saturation function is designed in the master side to guarantee the boundedness of the delayed environmental torque signal $\tau_e(t - T(t))$, which can effectively mitigate the negative effect of transmission delays on the system's stability. To produce the passive reference trajectory for the tracking of master manipulator and provide the human operator with good force feedback, a reference trajectory producer is designed in the master side. Subsequently, the RBFNN-based adaptive sliding mode controller is designed separately for the master and slave manipulator to achieve the good tracking performance. Thus, the global stability and good transparency performance including position tracking and force feedback is simultaneously achieved.

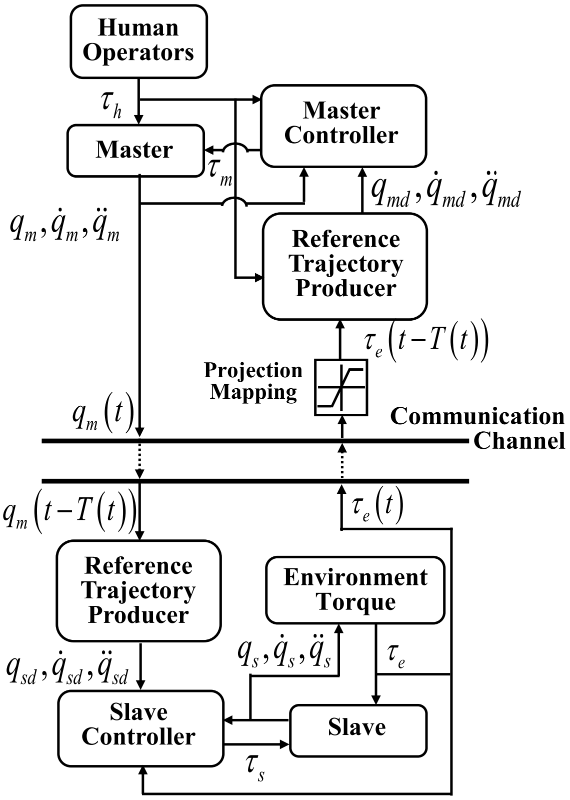

FIGURE 3. Control scheme of nonlinear bilateral teleoperation system.

B. SLAVE CONTROL DESIGN

A reference trajectory producer is designed in the slave, which is a low-pass filter $E_f(s) = 1/(\tau_f s + 1)$ with the input of delayed master position signal $q_m(t - T(t))$, to produce the reference trajectory $q_{sd}, \dot{q}_{sd}, \ddot{q}_{sd}$ for the tracking of slave manipulator.

Define the sliding surface as

$$s_s = \dot{e}_s + k_s e_s \tag{10}$$

where $k_s = k_s^T > 0$ and $e_s = q_{sd} - q_s$. Thus,

$$\begin{aligned} M_s \dot{s}_s &= M_s(\ddot{q}_{sd} + k_s \dot{e}_s) - M_s \ddot{q}_s \\ &= M_s(\ddot{q}_{sd} + k_s \dot{e}_s) + C_s \dot{q}_s + G_s + D_s - \tau_e - \tau_s \\ &= -C_s s_s + \phi_s + D_s - \tau_e - \tau_s \end{aligned} \tag{11}$$

where $\phi_s = M_s(\ddot{q}_{sd} + k_s\dot{e}_s) + C_s(\dot{q}_{sd} + k_s e_s) + G_s$, which contains the dynamic information of the slave manipulator.

Then, the slave controller τ_s can be designed as:

$$\tau_s = l_s s_s + \hat{\phi}_s + \eta_s sgn(s_s) - \tau_e \tag{12}$$

where $l_s > 0$, $\eta_s > 0$, $\hat{\phi}_s$ is the RBFNN to estimate the unknown dynamic parameters ϕ_s, and can be written as:

$$\hat{\phi}_s = \hat{W}_s h_s(x_s) + \varepsilon_s \tag{13}$$

where

$$\begin{aligned} x_s &= \begin{bmatrix} e_s^T & \dot{e}_s^T & \ddot{q}_{sd}^T \end{bmatrix} \\ h_{sj}(x_s) &= \exp\left(\frac{\|x_s - c_j\|^2}{2b_j^2}\right) \\ h_s(x_s) &= \left[h_{sj}(x_s)\right]^T \end{aligned}$$

$j = 1, \ldots, n$ is the hidden nodes of RBFNN, and ε_s is the estimation error satisfying $\varepsilon_s \leq \bar{\varepsilon}_s$.

And the adaptive law can be designed as:

$$\dot{\hat{W}}_s = \frac{1}{\delta_s} s_s h_s(x_s) \tag{14}$$

Therefore, the following theorem can be obtained as:

Theorem 1: With the bounded delayed signal $q_m(t - T(t))$ and $\eta_s \geq \bar{\varepsilon}_s + \bar{d}_s$, by utilizing the control law (12) and the adaptive law (14), all the signals in the slave are bounded with $e_s \to 0$, and the slave subsystem is asymptotically stable by the design of positive definite Lyapunov function $V_s = \frac{1}{2}s_s^T M_s s_s + \frac{1}{2}\delta_s \tilde{W}_s^T \tilde{W}_s$, where $\tilde{W}_s = W_s - \hat{W}_s$, $\delta_s > 0$. ■

Proof: Consider the following Lyapunov function V_s as:

$$V_s = \frac{1}{2}s_s^T M_s s_s + \frac{1}{2}\delta_s \tilde{W}_s^T \tilde{W}_s \tag{15}$$

Then the derivative of V_s is

$$\begin{aligned} \dot{V}_s &= s_s^T M_s \dot{s}_s + \frac{1}{2}s_s^T \dot{M}_s s_s + \delta_s \tilde{W}_s^T \dot{\tilde{W}}_s \\ &= s_s^T\left(\tilde{\phi}_s + \varepsilon_s + D_s - \eta_s sgn(s_s) - l_s s_s\right) \\ &\quad + \frac{1}{2}s_s^T\left(\dot{M}_s - 2C_s\right)s_s - \delta_s \tilde{W}_s^T \dot{\hat{W}}_s \\ &= -s_s^T l_s s_s + s_s^T(\varepsilon_s + D_s - \eta_s sgn(s_s)) \\ &\quad + \tilde{W}_s^T\left(s_s h_s(x_s) - \delta_s \dot{\hat{W}}_s\right) \end{aligned} \tag{16}$$

Substitute the adaptive law (14) to (16), then

$$\begin{aligned} \dot{V}_s &\leq -s_s^T l_s s_s + s_s^T(\varepsilon_s + D_s) - \left(\bar{d}_s + \bar{\varepsilon}_s\right)\|s_s\| \\ &\leq -s_s^T l_s s_s \end{aligned} \tag{17}$$

For $V_s \geq 0$ and $\dot{V}_s \leq 0$, V_s is bounded, which means s_s and $\tilde{W}_s$ are bounded. Furthermore, when $s_s = 0$, $\dot{V}_s = 0$, according to Lasalle invariance principle, the slave subsystem is asymptotically stable, and $s_s, e_s, \dot{e}_s \to 0$.

The proof is complete. □

C. MASTER CONTROL DESIGN

To provide the operator with the bounded environment force feedback transmitted from the slave side via the communication channel, a projection mapping by saturation function is used in the master side, which is to guarantee the boundedness of the delayed environmental torque $\tau_e(t - T(t))$.

Thus, based on the good control of master manipulator to let $q_m \to q_{md}$ and the bounded environmental torque, a reference trajectory producer is designed in the master side to produce the passive reference trajectory q_{md}, which can be written as:

$$\begin{aligned} M_r(q_{md})\ddot{q}_{md} &+ C_r(q_{md}, \dot{q}_{md})\dot{q}_{md} + G_r(q_{md}) \\ &= \tau_h - \tau_e(t - T(t)) \end{aligned} \tag{18}$$

where M_r, C_r and G_r are the impendence parameters.

Define the sliding surface as

$$s_m = \dot{e}_m + k_m e_m \tag{19}$$

where $k_m = k_m^T > 0$ and $e_m = q_{md} - q_m$. Thus,

$$\begin{aligned} M_m \dot{s}_m &= M_m(\ddot{q}_{md} + k_m \dot{e}_m) - M_m \ddot{q}_m \\ &= M_m(\ddot{q}_{md} + k_m \dot{e}_m) + C_m \dot{q}_m + G_m + D_m \\ &\quad - \tau_h - \tau_m \\ &= -C_m s_m + \phi_m + D_m - \tau_h - \tau_m \end{aligned} \tag{20}$$

where $\phi_m = M_m(\ddot{q}_{md} + k_m \dot{e}_m) + C_m(\dot{q}_{md} + k_m e_m) + G_m$, which contains the dynamic information of the master manipulator.

Then, the master controller τ_m can be designed as:

$$\tau_m = l_m s_m + \hat{\phi}_m + \eta_m sgn(s_m) - \tau_h \tag{21}$$

where $l_m > 0$, $\eta_m > 0$, $\hat{\phi}_m$ is the RBFNN to estimate the unknown dynamic parameters ϕ_m, and can be written as:

$$\hat{\phi}_m = \hat{W}_m h_m(x_m) + \varepsilon_m \tag{22}$$

where

$$\begin{aligned} x_m &= \begin{bmatrix} e_m^T & \dot{e}_m^T & \ddot{q}_{md}^T \end{bmatrix} \\ h_{mj}(x_m) &= \exp\left(\frac{\|x_m - c_j\|^2}{2b_j^2}\right) \\ h_m(x_m) &= \left[h_{mj}(x_m)\right]^T \end{aligned}$$

$j = 1, \ldots, n$ is the hidden nodes of the RBFNN, and ε_m is the estimation error, $\varepsilon_m \leq \bar{\varepsilon}_m$.

And the adaptive law can be designed as:

$$\dot{\hat{W}}_m = \frac{1}{\delta_m} s_m h_m(x_m) \tag{23}$$

Therefore, the following theorem can be obtained as:

Theorem 2: With the bounded delayed environment torque, passive reference trajectory produced in (18), and $\eta_m \geq \bar{\varepsilon}_m + \bar{d}_m$, by utilizing the control law (21) and the adaptive law (23), all the signals in the master is bounded with $e_m \to 0$, and the master subsystem is asymptotically stable by the design

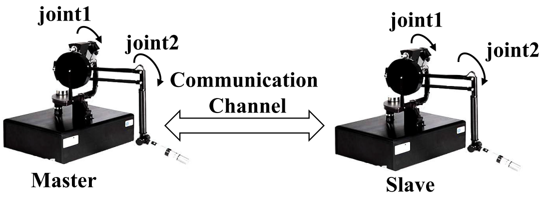

FIGURE 4. Test platform.

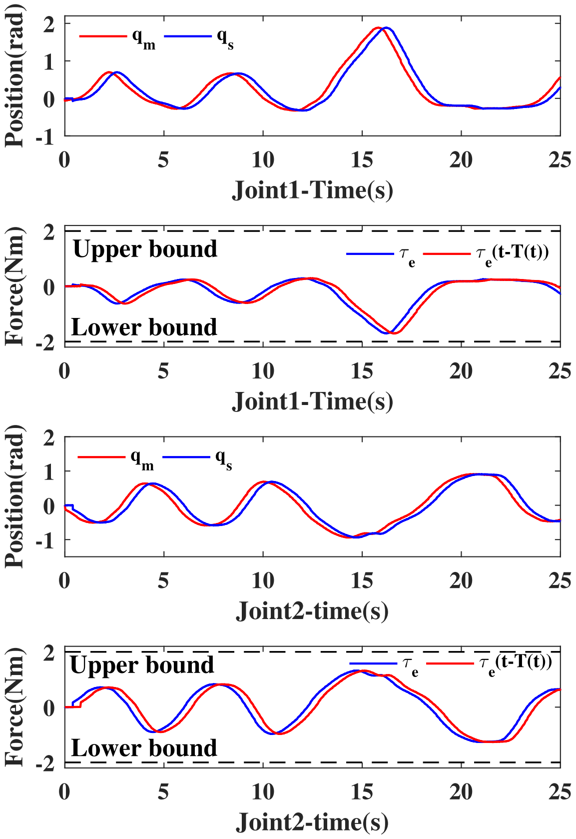

FIGURE 5. Transparency performance of C1.

of positive definite Lyapunov function $V_m = \frac{1}{2}s_m^T M_m s_m + \frac{1}{2}\delta_m \tilde{W}_m^T \tilde{W}_m$, where $\tilde{W}_m = W_m - \hat{W}_m$, $\delta_m > 0$. ■

Proof: Consider the following Lyapunov function V_m as:

$$V_s = \frac{1}{2}s_m^T M_m s_m + \frac{1}{2}\delta_m \tilde{W}_m^T \tilde{W}_m \tag{24}$$

Then the derivative of V_m is

$$\begin{aligned}
\dot{V}_m &= s_m^T M_m \dot{s}_m + \frac{1}{2}s_m^T \dot{M}_m s_m + \delta_m \tilde{W}_m^T \dot{\tilde{\mathbf{W}}}_m \\
&= s_m^T \left(\tilde{\phi}_m + D_m + \varepsilon_m - \eta_m sgn\left(s_m\right) - l_m s_m\right) \\
&\quad + \frac{1}{2}s_m^T \left(\dot{M}_m - 2C_m\right) s_m - \delta_m \tilde{W}_m^T \dot{\hat{\mathbf{W}}}_m \\
&= -s_m^T l_m s_m + s_m^T \left(D_m + \varepsilon_m - \eta_m sgn\left(s_m\right)\right) \\
&\quad + \tilde{W}_m^T \left(s_m h_m\left(x_m\right) - \delta_m \dot{\hat{\mathbf{W}}}_m\right)
\end{aligned} \tag{25}$$

Substitute the adaptive law (23) to (25), then

$$\begin{aligned}
\dot{V}_m &\leq -s_m^T l_m s_m + s_m^T \left(D_m + \varepsilon_m\right) - \left(\bar{d}_m + \bar{\varepsilon}_m\right)\|s_m\| \\
&\leq -s_m^T l_m s_m
\end{aligned} \tag{26}$$

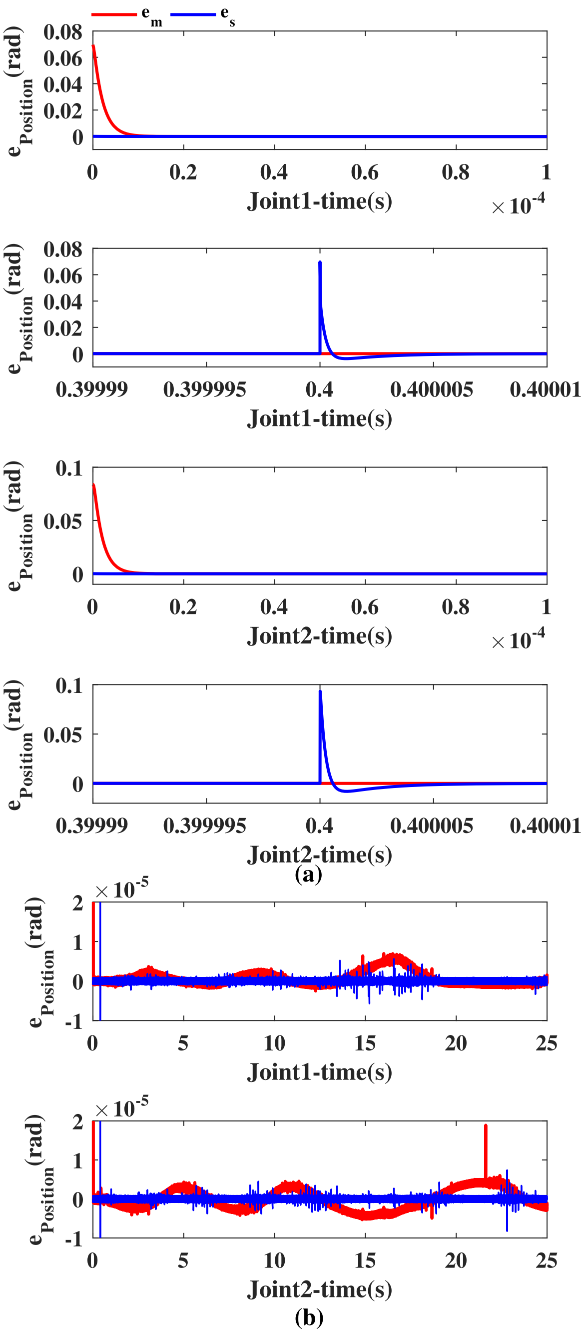

FIGURE 6. Position tracking errors of C1. (a) The initial-state transient response. (b) The steady-state error.

For $V_m \geq 0$ and $\dot{V}_m \leq 0$, V_m is bounded, which means s_m and $\tilde{W}_m$ are bounded. Furthermore, when $s_m = 0$, $\dot{V}_m = 0$, according to Lasalle invariance principle, the slave subsystem is asymptotically stable, and $s_m, e_m, \dot{e}_m \to 0$.

The proof is complete. ☐

Therefore, the following remarks can be obtained as:

Remark 1: With the saturated projection mapping to guarantee the boundedness of delayed environmental torque, the signals in the whole teleoperation system are bounded. Moreover, with the asymptotically stable of master and slave

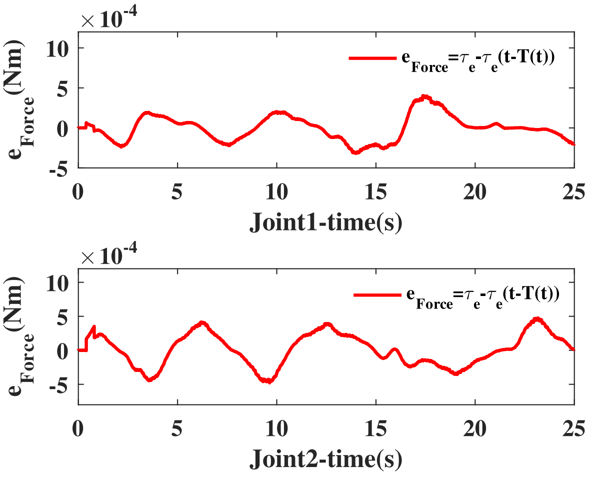

FIGURE 7. Force feedback errors of C1.

subsystems guaranteed separately by Theorem 1 and Theorem 2, the overall closed-loop bilateral teleoperation system is stable. ■

Remark 2: The good position tracking performance is achieved with the convergence of reference trajectory q_{sd} to $q_m(t - T(t))$ via the stable low-pass filter $E_f(s)$ and the good tracking performance of slave manipulator guaranteed by Theorem 1. Moreover, the good force feedback performance is achieved with the good impedance behavior in (18). Therefore, the good transparency performance including position tracking and force feedback is achieved. ■

V. EXPERIMENT

A. EXPERIMENT SETUP

The Phantom Premium haptic devices are the real test platform for our nonlinear bilateral teleoperation system, which are shown in Fig.4. Each device offers 6 degrees of freedom (3 translational, 3 rotational) in output, and is suitable for the maintenance of trajectory planning and teleoperation applications.

In the experiment, to verify the transparency performance improvement for nonlinear master/slave manipulators in the teleoperation system under time-varying delays, the Joint 1 and Joint 2 of the Premium haptic devices are used, and the time-varying delays are selected as $0.4 \pm 0.1s$. The disturbance and modeling error are set as $D_m = D_s = [0.05 \sin t, 0.05 \sin t]^T$.

The experiment with human-enforced motion references is implemented, where the following two controllers are used for the fair comparison as:

C1: The proposed controller with RBFNN-based ASMC and saturated projection mapping. The control law and adaptive law for the master manipulator are selected as (12) and (14), where $\eta_m = 0.25$, $\delta_m = 0.05$, $l_m = k_m = diag\{15, 15\}$. The impendence parameters are selected as $M_r = diag\{1.5, 1.5\}$, $C_r = diag\{0, 0\}$, $G_r = diag\{2*9.8, 2*9.8\} * q_{md}$. The control law and adaptive law for the slave manipulator are selected as (21) and (23), where $\eta_s = 0.25$, $\delta_s = 0.05$, $l_s = k_s = diag\{15, 15\}$. The τ_f in the low-pass filter is set as $\tau_f = 0.025$. The upper and lower bounds of the saturation function are set as ± 2 Nm. In the RBFNN, the hidden nodes are selected as $n = 5$, $b_j = 0.5$, and C is selected as:

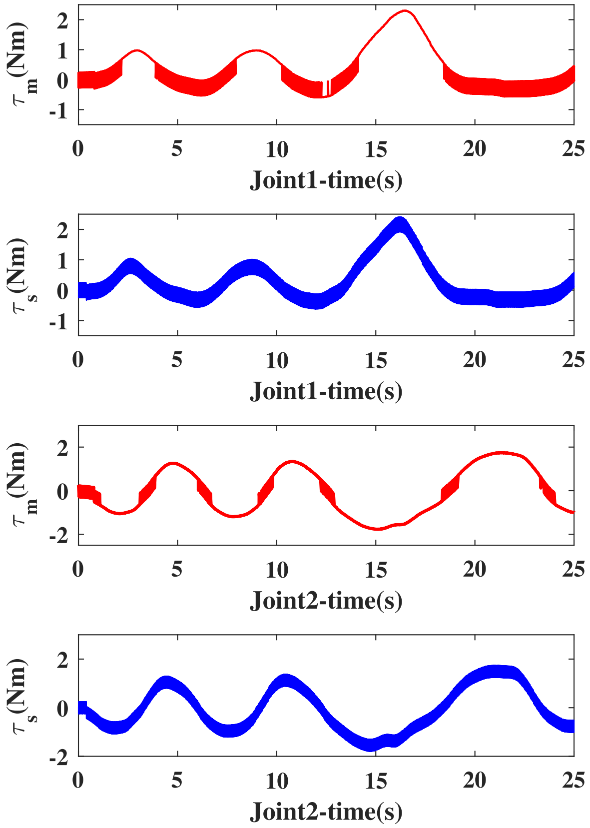

FIGURE 8. Control inputs of C1.

$$C = \begin{bmatrix} -1.0 & -0.5 & 0 & 0.5 & 1.0 \\ -1.0 & -0.5 & 0 & 0.5 & 1.0 \\ -1.0 & -0.5 & 0 & 0.5 & 1.0 \end{bmatrix} \tag{27}$$

C2: The traditional PD control and without the projection mapping. The parameters of PD control are selected as $k_p = diag\{0.5, 0.5\}$, $k_d = diag\{10, 10\}$.

B. EXPERIMENT RESULT

Fig.5-9 show the comparative results of transparency performance with two different controllers.

It can be clearly seen that the position and force signals of the slave manipulator go up to infinity after 7s in Fig.9, which means the system is not stable with C2 under time-varying delays.

Since the implement of projection mapping in C1, the delayed environmental torque signal is bounded (shown in Fig.5), which guarantees the whole signals in the teleoperation system to be bounded. Moreover, with the enrollment of sliding mode control design and the bounded control inputs (shown in Fig.8), the system has the greater transient response performance, where the convergence time is fast with small

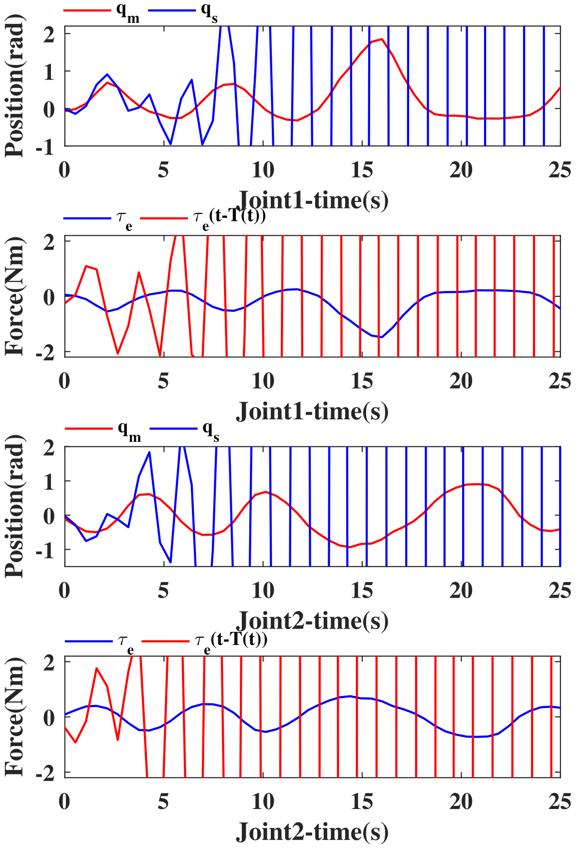

FIGURE 9. Transparency performance of C2.

orders of magnitude ($10^{-5}s$, shown in Fig.6(a)), and the position tracking error (shown in Fig.6) and force feedback errors (shown in Fig.7) are quite small.

Therefore, the slave can greatly track the master and provide the human operator with accurate force feedback, even when the joint 1 of manipulator reach a large position at about 16s, which validates the effectiveness of our control design in the improvement of transparency performance for nonlinear bilateral teleopration system with time-varying delays.

VI. CONCLUSION

In this paper, an RBFNN-based adaptive sliding mode control design is proposed for nonlinear bilateral teleoperation system with transmission delays and uncertainties. The reference trajectory producer is designed in both the master and slave sides to produce the passive reference trajectories for the tracking of master/slave manipulators, and the RBFNN-based adaptive sliding mode controller is designed separately for the master and slave to achieve the good tracking performance under system uncertainties. A projection mapping by saturation function is applied in the master side to guarantee the boundedness of the delayed environmental torque, which mitigates the negative effect of transmission delays on the system's stability. Thus, the global stability and good transparency performance including position tracking and force feedback can be simultaneously obtained for our proposed method. Comparative investigation is carried out and the results show that the transparency performance with both position tracking and force feedback is significantly improved by using our proposed control design, while the stability is still guaranteed in the presence of time-varying delays.

REFERENCES

[1] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, Dec. 2006.

[2] Z. Chen, B. Yao, and Q. Wang, "Accurate motion control of linear motors with adaptive robust compensation of nonlinear electromagnetic field effect," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 3, pp. 1122–1129, Jun. 2013.

[3] H. Liang, L. Zhang, H. R. Karimi, and Q. Zhou, "Fault estimation for a class of nonlinear semi-Markovian jump systems with partly unknown transition rates and output quantization," *Int. J. Robust Nonlinear Control*, vol. 28, no. 3, pp. 5962–5980, Oct. 2018.

[4] M. Yuan, Z. Chen, B. Yao, and X. Zhu, "Time optimal contouring control of industrial biaxial gantry: A high-efficient analytical solution of trajectory planning," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 247–257, Feb. 2017.

[5] C. Li, C. Li, Z. Chen, and B. Yao, "Advanced synchronization control of a dual-linear-motor-driven gantry with rotational dynamics," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7526–7535, Sep. 2018.

[6] W. Sun, Y. Zhang, Y. Huang, H. Gao, and O. Kaynak, "Transient-performance-guaranteed robust adaptive control and its application to precision motion control systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6510–6518, Mar. 2016.

[7] W. Sun, S. Tang, H. Gao, and J. Zhao, "Two time-scale tracking control of nonholonomic wheeled mobile robots," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 6, pp. 2059–2069, Nov. 2016.

[8] J. Yao and W. Deng, "Active disturbance rejection adaptive control of hydraulic servo systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8023–8032, Oct. 2017.

[9] J. Yao, W. Deng, and Z. Jiao, "RISE-based adaptive control of hydraulic systems with asymptotic tracking," *IEEE Trans. Automat. Sci. Eng.*, vol. 14, no. 3, pp. 1524–1531, Jul. 2015.

[10] A. Haddadi, K. Razi, and K. Hashtrudi-Zaad, "Operator dynamics consideration for less conservative coupled stability condition in bilateral teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2463–2475, Oct. 2015.

[11] S. Qiu, Z. Li, W. He, L. Zhang, C. Yang, and C.-Y. Su, "Brain–machine interface and visual compressive sensing-based teleoperation control of an exoskeleton robot," *IEEE Trans. Fuzzy Syst.*, vol. 25, no. 1, pp. 58–69, Feb. 2017.

[12] M. Rank, Z. Shi, H. J. Müller, and S. Hirche, "Predictive communication quality control in haptic teleoperation with time delay and packet loss," *IEEE Trans. Human-Mach. Syst.*, vol. 46, no. 4, pp. 581–592, Aug. 2016.

[13] H. Li and K. Kawashima, "Achieving stable tracking in wave-variable-based teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 5, pp. 1574–1582, Oct. 2014.

[14] C. Hua, Y. Yang, and P. X. Liu, "Output-feedback adaptive control of networked teleoperation system with time-varying delay and bounded inputs," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2009–2020, Oct. 2015.

[15] Z. Chen, F. Huang, W. Sun, and W. Song, "An Improved wave-variable based four-channel control design in bilateral teleoperation system for time-delay compensation," *IEEE Access*, vol. 6, pp. 12848–12857, 2018.

[16] X. Yang, C.-C. Hua, J. Yan, and X.-P. Guan, "A new master-slave torque design for teleoperation system by T-S fuzzy approach," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 4, pp. 1611–1619, Jul. 2015.

[17] Z. Lu, P. Huang, and Z. Liu, "Predictive approach for sensorless bimanual teleoperation under random time delays with adaptive fuzzy control," *Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2439–2448, Mar. 2018.

[18] Z. Chen, F. Huang, W. Song, and S. Zhu, "A novel wave-variable based time-delay compensated four-channel control design for multilateral teleoperation system," *IEEE Access*, vol. 6, pp. 25506–25516, 2018.

[19] Z. Chen, Y.-J. Pan, and J. Gu, "A novel adaptive robust control architecture for bilateral teleoperation systems under time-varying delays," *Int. J. Robust Nonlinear Control*, vol. 25, no. 17, pp. 3349–3366, Nov. 015.

[20] R. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May 1989.

[21] R. J. Anderson and M. W. Spong, "Asymptotic stability for force reflecting teleoperators with time delay," *Int. J. Robot. Res.*, vol. 11, no. 2, pp. 135–149, Apr. 1992.

[22] Y. Ye, Y.-J. Pan, Y. Gupta, and J. Ware, "A power-based time domain passivity control for haptic interfaces," *IEEE Trans. Control Syst. Technol.*, vol. 19, no. 4, pp. 874–883, Jul. 2011.

[23] G. Niemeyer and J.-J.-E. Slotine, "Stable adaptive teleoperation," *IEEE J. Ocean. Eng.*, vol. 16, no. 1, pp. 152–162, Jan. 1991.

[24] M. Tong, Y. Pan, Z. Li, and W. Lin, "Valid data based normalized cross-correlation (VDNCC) for topography identification," *Neurocomputing*, vol. 308, pp. 184–193, Sep. 2018.

[25] K. Hashtrudi-Zaad and S. E. Salcudean, "Transparency in time-delayed systems and the effect of local force feedback for transparent teleoperation," *IEEE Trans. Robot. Autom.*, vol. 18, no. 1, pp. 108–114, Feb. 2002.

[26] B. Yalcin and K. Ohnishi, "Stable and transparent time-delayed teleoperation by direct acceleration waves," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3228–3238, Sep. 2010.

[27] Q.-F. Liao and D. Sun, "Interaction measures for control configuration selection based on interval type-2 Takagi–Sugeno fuzzy model," *IEEE Trans. Fuzzy Syst.*, vol. 26, no. 5, pp. 2510–2523, Oct. 2018.

[28] C. P. Bechlioulis, Z. Doulgeri, and G. A. Rovithakis, "Neuro-adaptive force/position control with prescribed performance and guaranteed contact maintenance," *IEEE Trans. Neural Netw.*, vol. 21, no. 12, pp. 1857–1868, Dec. 2010.

[29] A. K. Kostarigka and G. A. Rovithakis, "Adaptive dynamic output feedback neural network control of uncertain MIMO nonlinear systems with prescribed performance," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 23, no. 1, pp. 138–149, Jan. 2012.

[30] Y. Zhang, J. Sun, H. Liang, and H. Li, "Event-triggered adaptive tracking control for multiagent systems with unknown disturbances," *IEEE Trans. Cybern.*, to be published, doi: 10.1109/TCYB.2018.2869084.

[31] Y. Yang, C. Hua, H. Ding, and H. Ding, "Finite-time coordination control for networked bilateral teleoperation," *Robotica*, vol. 33, no. 2, pp. 451–462, Feb. 2015.

[32] Y. Yang, C. Hua, and X. Guan, "Finite time control design for bilateral teleoperation system with position synchronization error constrained," *IEEE Trans. Cybern.*, vol. 46, no. 3, pp. 609–619, Mar. 2016.

[33] D. Sun, F. Naghdy, and H. Du, "Neural network-based passivity control of teleoperation system under time-varying delays," *IEEE Trans. Cybern.*, vol. 47, no. 7, pp. 1666–1680, Jul. 2017.

[34] D. Sun, Q. Liao, and H. Ren, "Type-2 fuzzy modeling and control for bilateral teleoperation system with dynamic uncertainties and time-varying delays," *IEEE Trans. Ind. Electron.*, vol. 65, no. 1, pp. 447–459, Jan. 2018.

[35] Z. Chen, Y.-J. Pan, and J. Gu, "Integrated adaptive robust control for multilateral teleoperation systems under arbitrary time delays," *Int. J. Robust Nonlinear Control*, vol. 26, no. 12, pp. 2439–2448, Aug. 2016.

[36] G.-B. Huang, P. Saratchandran, and N. Sundararajan, "A generalized growing and pruning RBF (GGAP-RBF) neural network for function approximation," *IEEE Trans. Neural Netw.*, vol. 16, no. 1, pp. 57–67, Jan. 2005.

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