

A Novel Multilateral Control Design for Delayed Nonlinear Teleoperation System With RBFNN-based Environments^{*}

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Abstract: In this paper, a novel multilateral control design for nonlinear teleoperation system is proposed to improve the capability of multiple robots to coordinate efficiently and precisely in the remote environments under time-varying delays and various uncertainties. The environment is modeled with a general form of force under radial basis function neural network(RBFNN)-based identification and reconstruction to avoid the passivity issue in the traditional teleoperation control and provide the human operators with good sensing of environments. The desired trajectory producers and RBFNN-based sliding mode controllers are designed separately to achieve the good tracking of master/slave robots, and the coordinated distribution algorithm is designed to obtain the control input $u_{s,i}$ for each slave robot. Therefore, the global stability, good transparency performance with both position tracking and force feedback, and good cooperative performance can be achieved simultaneously for delayed nonlinear teleoperation system. The real platform experiment is carried out on a 2-master-2-slave teleoperation system to verify the effectiveness of proposed control design.

Keywords: Multilateral teleoperation, Neural network, Good transparency, Cooperative manipulation

1. INTRODUCTION

The multilateral teleoperation technique, which is regarded as an extension of bilateral teleoperation technique with force feedback, aims to improve the ability of multiple master and slave robots to implement some complicated tasks in dangerous and remote environment (Rebello and Schiele, 2015) (Chen *et al.*, 2016), and has been applied in many fields (Hou and Mahony, 2016) (Takhmar *et al.*, 2015) (Rank *et al.*, 2016). Typically, the multilateral teleoperation system consists of the multiple human operators, masters, slaves, communication channel and the working environments (Huang *et al.*, 2018).

Since the multilateral teleoperation is a relatively new concept, few control designs have been considered in the latest publications and have not been well developed yet (Chen *et al.*, 2019). For example, a μ -synthesis-based algorithm for teleoperation system was proposed to guarantee the stability under dynamic interaction between cooperative slave robots (Sirouspour, 2005); an observation method of the reaction force for multiple robots was proposed to control a natural motion of contact for integrated multilateral teleoperation system (Lo *et al.*, 2004); a six-channel multilateral control architecture was proposed that the

two operators or the slave and environment were allowed to interact through a dominance factor that adjusts the authority of the users over the slave robot and environment (Khademian *et al.*, 2012). However, all the aforementioned control designs don't consider the time delay existing in the communication channel, which even exacerbates the problem of system's stability.

A number of passivity-based control methods have been applied to cope with the instability problem of bilateral teleoperation system due to time delay in communication channel (Sun *et al.*, 2017). Namely, the stabilization method for teleoperation system under time delay based on the scattering operator and two-port network theory (Anderson and Spong, 1989), the wave-variable based control scheme (Niemeyer and Slotine, 1991), the time-domain passivity control scheme (Hannaford and Ryu, 2002) and the power-based time-domain passivity control scheme (Ye *et al.*, 2011) were proposed to guaranteed the system's stability. However, there will be more challenges when extending the problem to the multilateral conditions as the communication channel between multiple masters and slaves becomes more complex, and the above methods may not be sufficient. Therefore, the wave node was proposed for multilateral teleoperation system, where multiple wave-variable-based transmission lines were connected, and the stability of system was maintained (Kanno and Yokokohji, 2012). The extended power-based time-domain passivity control design for multilateral teleoperation system was

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proposed and the weighing coefficients were designed to act on different masters or slaves with weighted effects. (Chen *et al.*, 2016).

Recently, with the development of automation, more complicated tasks are implemented in the remote and hazardous environments, which need multiple robots with nonlinearities and various uncertainties to handle the targets. Therefore, higher demands to achieve good transparency and cooperative performance are placed on the control design for this kind of teleoperation system (Farooq *et al.*, 2017). Focused on these significant issues, a novel multilateral control design for nonlinear teleoperation system is proposed in this paper to improve the ability of multiple robots to coordinate efficiently and accurately in the remote environments under time-varying delays and various uncertainties. The environment is modeled in a general form of force under RBFNN-based identification and reconstruction to avoid the passivity issue in the traditional teleoperation control and provide the human operators with good sensing of environments. The desired trajectory producers and RBFNN-based sliding mode controllers are designed separately to achieve the good tracking of master/slave robots, and the coordinated distribution algorithm is designed to obtain the control input $u_{s,i}$ for each slave robot. Therefore, the global stability, good transparency performance with both position tracking and force feedback, and good cooperative performance can be achieved simultaneously for delayed nonlinear teleoperation system. The real platform experiment is carried out on a 2-master-2-slave teleoperation system, and verifies the effectiveness of proposed method in the improvement of simultaneously achieving the stability, good transparency and cooperative performance.

2. MODELING FOR MULTILATERAL TELEOPERATION SYSTEM

Consider the i -th master robot as the second-order nonlinear system, which can be written as:

$$\ddot{x}_{m,i} = \alpha_{m,i}\dot{x}_{m,i} + \beta_{m,i}x_{m,i} + u_{m,i} + F_{h,i} + d_{m,i} \quad (1)$$

where $i = 1, \dots, n$, $\alpha_{m,i}$, $\beta_{m,i}$ are the unknown but bounded parameters, $x_{m,i}$, $\dot{x}_{m,i}$, $\ddot{x}_{m,i}$ are the displacement, velocity and acceleration of the i -th master robot. $u_{m,i}$ is the control input, $F_{h,i}$ is the operation force, $d_{m,i}$ is the external disturbance, respectively.

Since the target is grasped by the multiple slave robots, the dynamics combining the slaves and target can be written as:

$$\ddot{x}_{s,o} = \alpha_{s,o}\dot{x}_{s,o} + \beta_{s,o}x_{s,o} + u_s - F_e + d_s \quad (2)$$

and the relationship between the target and i -th slave robot can be defined as:

$$\begin{aligned} x_{s,o} &= K_{o,i}(x_{s,i}) \\ \dot{x}_{s,o} &= \frac{dK_{o,i}(x_{s,i})}{dx_{s,i}} \dot{x}_{s,i} \\ \ddot{x}_{s,o} &= \frac{d^2K_{o,i}(x_{s,i})}{dx_{s,i}^2} \dot{x}_{s,i}^2 + \frac{dK_{o,i}(x_{s,i})}{dx_{s,i}} \ddot{x}_{s,i} \end{aligned} \quad (3)$$

where $\alpha_{s,o}$, $\beta_{s,o}$ are the unknown but bounded parameters, $x_{s,o}$, $\dot{x}_{s,o}$, $\ddot{x}_{s,o}$ and $x_{s,i}$, $\dot{x}_{s,i}$, $\ddot{x}_{s,i}$ are the displacement, velocity and acceleration of target and i -th slave robot, u_s is the control input, F_e is the environment force between

the slave robot and target, d_s is the external disturbance, respectively. $K_{o,i}(\bullet)$ means $x_{s,o}$ is the function of $x_{s,i}$.

Some properties and assumptions of (1) and (2) are listed as follows:

Property 1 : Part of (1) and (2) is linear and can be written in the form of RBFNN as:

$$\alpha_{m,i}\dot{x}_{m,i} + \beta_{m,i}x_{m,i} = W_{m,i}^T h(x_{m,i}, \dot{x}_{m,i}, \ddot{x}_{m,i}) \quad (4)$$

$$\alpha_{s,o}\dot{x}_{s,o} + \beta_{s,o}x_{s,o} = W_s^T h(x_{s,o}, \dot{x}_{s,o}, \ddot{x}_{s,o}) \quad (5)$$

where $\dot{x}_{md,i}$, $\dot{x}_{sd,o}$ and $\ddot{x}_{md,o}$, $\ddot{x}_{sd,o}$ are the desired velocities and accelerations of i -th master robot and target.

Assumption 1 : The external disturbances $d_{m,i}$ and d_s are bounded with:

$$|d_{m,i}| \leq \bar{D}_{m,i}, |d_s| \leq \bar{D}_s \quad (6)$$

The RBFNN algorithm is used to model the environment dynamics F_e in a general form, which can describe different environments, and can be written as:

$$F_e = W_e^T h(x_{s,o}, \dot{x}_{s,o}, \ddot{x}_{s,o}) \quad (7)$$

where W_e is the unknown environment parameters to be identified.

3. NOVEL CONTROL DESIGN FOR MULTILATERAL TELEOPERATION SYSTEM

3.1 System architecture

The architecture for multilateral teleoperation system is shown in Fig.1, which includes the identification and reconstruction of environment dynamics to identify the environment parameters and provide the force feedback for human operators, the desired trajectory producers to produce the desired trajectories for the master/slave robots' tracking, the RBFNN-based sliding mode controllers for the good tracking of master/slave robots with nonlinearities and uncertainties, and the coordinated distribution algorithm to obtain the control input $u_{s,i}$ for each slave robot.

3.2 Identification of environment dynamics

Different from the power signal's transmission in the traditional teleoperation system, the environment parameters are identified based on the RBFNN algorithm, which is the non-power signal and can be transmitted to the master side to reconstruct the environment force. Therefore, the passivity issue in the previous teleoperation control can be avoided, and the environment force feedback can be provided for the human operator. The detailed design is in the following.

According to (7), the environment force F_e can be defined in a general form under the RBFNN algorithm as:

$$F_e = W_e^T h(\phi_e) \quad (8)$$

where W_e is the unknown environment parameters, ϕ_e is related to $x_{s,o}$, $\dot{x}_{s,o}$ and $\ddot{x}_{s,o}$.

Based on the environment force (8) and the RBFNN algorithm, the optimal environment parameters \hat{W}_e can be derived as:

$$\hat{W}_e = \arg \min_{W_e \in \Xi_{e0}} \left[\sup_{\phi_e \in \Xi_e} |W_e^T h(\phi_e) - \hat{W}_e^T h(\phi_e)| \right] \quad (9)$$

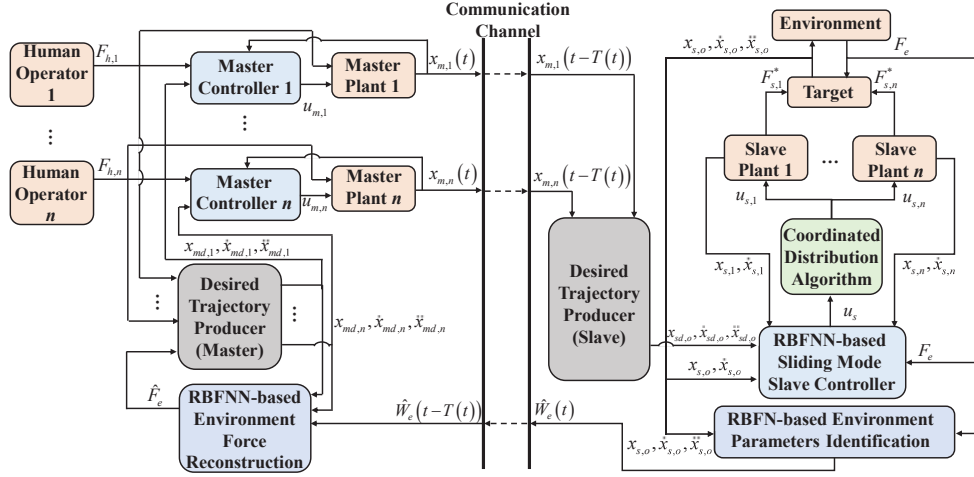


Fig. 1. The architecture for multilateral teleoperation system.

where Ξ_{e0} and Ξ_e are the bounded sets of W_e and ϕ_e .

Subsequently, the optimal environment parameters \hat{W}_e are identified by neural network toolbox in Matlab, where the input is ϕ_e and the output is F_e measured by the force sensor.

After the identification of environment force F_e , the non-power parameters \hat{W}_e are transmitted through the delayed communication channel to reconstruct the environment force in the master side, where the reconstructed environment force can be written as:

$$\hat{F}_e = \hat{W}_e(t - T(t))^T h(\phi_{m,e}) \quad (10)$$

where $\phi_{m,e}$ is related to $x_{md,i}$, $\dot{x}_{md,i}$ and $\ddot{x}_{md,i}$.

3.3 Control for master robots

To produce the desired tracking trajectory for i-th master robot and provide the human operators with force feedback from the environment, the trajectory planner is designed in the master subsystem as:

$$\begin{aligned} \ddot{x}_{md,o} + \alpha_{d,o}\dot{x}_{md,o} + \beta_{d,o}x_{md,o} \\ = \sum_{i=1}^n \frac{dK_{o,i}^{-T}}{dx_{md,o}} F_{h,i} - \hat{F}_e \end{aligned} \quad (11)$$

$$x_{md,i} = K_{o,i}^{-T}(x_{md,o}) \quad (12)$$

where $\alpha_{d,o}$ and $\beta_{d,o}$ are the selected parameters, $x_{md,o}$ is the virtual master trajectory, and $x_{md,i}$ is the desired trajectory for the tracking of i-th master robot.

Subsequently, the RBFNN-based control design for the i-th master robot is designed to satisfy $x_{m,i} \rightarrow x_{md,i}$, and the detailed design is in the following.

Define the sliding surface $s_{m,i}$ as:

$$s_{m,i} = \dot{e}_{m,i} + r_{m,i}e_{m,i} \quad (13)$$

where $r_{m,i} > 0$, $e_{m,i} = x_{m,i} - x_{md,i}$.

Subsequently, the derivative of $s_{m,i}$ can be calculated as:

$$\begin{aligned} \dot{s}_{m,i} &= r_{m,i}\dot{e}_{m,i} + \ddot{e}_{m,i} = r_{m,i}\dot{e}_{m,i} + \ddot{x}_{m,i} - \ddot{x}_{md,i} \\ &= r_{m,i}\dot{e}_{m,i} + \sigma_{m,i} + u_{m,i} + F_{h,i} + d_{m,i} - \ddot{x}_{md,i} \end{aligned} \quad (14)$$

where $\sigma_{m,i} = \alpha_{m,i}\dot{x}_{m,i} + \beta_{m,i}x_{m,i}$.

Based on (14), the control law $u_{m,i}$ for the i-th master robot can be designed as:

$$u_{m,i} = \ddot{x}_{md,i} - r_{m,i}\dot{e}_{m,i} - \nu_{m,i}s_{m,i} - \lambda_{m,i}sgn(s_{m,i}) - F_{h,i} - \hat{\sigma}_{m,i} \quad (15)$$

where $\nu_{m,i} > 0$, $\lambda_{m,i} > 0$, $\hat{\sigma}_{m,i}$ is based on the RBFNN algorithm, and can be written as:

$$\hat{\sigma}_{m,i} = \hat{W}_{m,i}^T h(\phi_{m,i}) + \varepsilon_{m,i} \quad (16)$$

where

$$\begin{aligned} \phi_{m,i} &= [e_{m,i}, \dot{e}_{m,i}, \ddot{x}_{md,i}]^T, \\ h_{j,i}(\phi_{m,i}) &= \exp\left(-\frac{\|\phi_{m,i} - c_{j,i}\|^2}{2b_{j,i}^2}\right), \end{aligned}$$

$h(\phi_{m,i}) = [h_{1,i}(\phi_{m,i}), \dots, h_{j,i}(\phi_{m,i}), \dots, h_{y,i}(\phi_{m,i})]^T$, $j = 1, \dots, y$ is the hidden node of RBFNN, and ε_m is identification error, $\varepsilon_{m,i} \leq \bar{\varepsilon}_{m,i}$.

Subsequently, the adaptive law to update the $\hat{W}_{m,i}$ online and real time, can be designed as:

$$\dot{\hat{W}}_{m,i} = \Gamma_{m,i}s_{m,i}h(\phi_{m,i}) \quad (17)$$

Therefore, in order to guarantee the stability of master subsystem, the following theorem can be obtained as:

Theorem 1. $\forall \lambda_{m,i} \geq \bar{\varepsilon}_{m,i} + \bar{D}_{m,i}$, by applying the control law (15) and the adaptive law (17), all the signals in the master subsystem are bounded with $e_{m,i} \rightarrow 0$ as $t \rightarrow \infty$, and the master subsystem is asymptotically stable.

Proof: Define the Lyapunov function $V_{m,i}$ as:

$$V_{m,i} = \frac{1}{2}s_{m,i}^2 + \frac{1}{2\Gamma_{m,i}}\tilde{W}_{m,i}^T\tilde{W}_{m,i} \quad (18)$$

where $\tilde{W}_{m,i} = W_{m,i} - \hat{W}_{m,i}$.

Subsequently, the derivative of $V_{m,i}$ can be derived as:

$$\begin{aligned} \dot{V}_{m,i} &= s_{m,i}\dot{s}_{m,i} + \frac{1}{\Gamma_{m,i}}\tilde{W}_{m,i}^T\dot{\tilde{W}}_{m,i} \\ &= s_{m,i}(r_{m,i}\dot{e}_{m,i} + \sigma_{m,i} + u_{m,i} + F_{h,i} + d_{m,i} - \ddot{x}_{md,i}) \\ &\quad - \frac{1}{\Gamma_{m,i}}\tilde{W}_{m,i}^T\dot{\tilde{W}}_{m,i} \end{aligned} \quad (19)$$

Substitute (15) into (19), then (19) can be derived as:

$$\begin{aligned}\dot{V}_{m,i} &= s_{m,i}(\sigma_{m,i} - \hat{\sigma}_{m,i} - \nu_{m,i}s_{m,i} - \lambda_{m,i}\text{sgn}(s_{m,i}) + d_{m,i}) \\ &\quad - \frac{1}{\Gamma_{m,i}}\tilde{W}_{m,i}^T\dot{\hat{W}}_{m,i} \\ &= -\nu_{m,i}s_{m,i}^2 + s_{m,i}(\varepsilon_{m,i} + d_{m,i} - \lambda_{m,i}\text{sgn}(s_{m,i})) \\ &\quad + \tilde{W}_{m,i}^T(s_{m,i}h(\phi_{m,i}) - \frac{1}{\Gamma_{m,i}}\dot{\hat{W}}_{m,i})\end{aligned}\quad (20)$$

Substitute (16) into (20), then (20) can be derived as:

$$\begin{aligned}\dot{V}_{m,i} &\leq -\nu_{m,i}s_{m,i}^2 + s_{m,i}(\varepsilon_{m,i} + d_{m,i}) - (\bar{\varepsilon}_{m,i} \\ &\quad + \bar{D}_{m,i}) |s_{m,i}| \\ &\leq -\nu_{m,i}s_{m,i}^2\end{aligned}\quad (21)$$

According to the above analysis, $V_{m,i} \geq 0$ and $\dot{V}_{m,i} \leq 0$, which means $V_{m,i}$ is bounded, and $s_{m,i}$ and $\hat{\sigma}_{m,i}$ are bounded. Moreover, as $s_{m,i} \equiv 0$ when $\dot{V}_{m,i} \equiv 0$, the master subsystem is asymptotically stable (w.r.t. Lasalle invariance principle). Therefore, $s_{m,i} \rightarrow 0$ and $e_{m,i}, \dot{e}_{m,i} \rightarrow 0$ as $t \rightarrow \infty$. The proof is complete.

3.4 Control for slave robots

To produce the desired tracking trajectory for the target, the trajectory planner is designed in the slave subsystem as:

$$U_f(s) = \frac{1}{(1 + \tau_f s)^2} \quad (22)$$

which is a low-pass filter with the input of delayed average master trajectory, and the desired target trajectory $x_{sd,o}$ can be derived as (Yao *et al.*, 1997):

$$x_{sd,o}(t) = U_f(s) \left[\frac{1}{n} \sum_{i=1}^n K_{o,i}(x_{m,i}(t - T(t))) \right] \quad (23)$$

Subsequently, the RBFNN-based control design for the slave robots and target is designed to satisfy $x_{s,o} \rightarrow x_{sd,o}$, and the detailed design is in the following.

Define the sliding surface s_s as:

$$s_s = \dot{e}_s + r_s e_s \quad (24)$$

where $r_s > 0$, $e_s = x_{s,o} - x_{sd,o}$.

Subsequently, the derivative of s_s can be calculated as:

$$\begin{aligned}\dot{s}_s &= r_s \dot{e}_s + \ddot{e}_s = r_s \dot{e}_s + \ddot{x}_{s,o} - \ddot{x}_{sd,o} \\ &= r_s \dot{e}_s + \sigma_s + u_s - F_e + d_s - \ddot{x}_{sd,o}\end{aligned}\quad (25)$$

where $\sigma_s = \alpha_{s,o}\dot{x}_{s,o} + \beta_{s,o}x_{s,o}$.

Based on (25), the control law u_s for the slave subsystem can be designed as:

$$u_s = \ddot{x}_{sd,o} - r_s \dot{e}_s - \nu_s s_s - \lambda_s \text{sgn}(s_s) + F_e - \hat{\sigma}_s \quad (26)$$

where $\nu_s > 0$, $\lambda_s > 0$, $\hat{\sigma}_s$ is based on the RBFNN algorithm to identify the unknown parameter σ_s in (25), which is written as:

$$\hat{\sigma}_s = \hat{W}_s^T h(\phi_s) + \varepsilon_s \quad (27)$$

where

$$\begin{aligned}\phi_s &= [e_s, \dot{e}_s, \ddot{x}_{sd,o}]^T, \\ h_{j,o}(\phi_s) &= \exp\left(\frac{\|\phi_s - c_{j,o}\|^2}{2b_{j,o}^2}\right), \\ h(\phi_s) &= [h_{1,o}(\phi_{m,i}), \dots, h_{j,o}(\phi_s), \dots, h_{y,o}(\phi_s)]^T,\end{aligned}$$

$j = 1, \dots, y$ is the hidden node of RBFNN, and ε_s is identification error, $\varepsilon_s \leq \bar{\varepsilon}_s$.

Subsequently, the adaptive law to update the \hat{W}_s online and real time, can be designed as:

$$\dot{\hat{W}}_s = \Gamma_s s_s h(\phi_s) \quad (28)$$

Therefore, to guarantee the stability of slave subsystem, the following theorem can be obtained as:

Theorem 2. $\forall \lambda_s \geq \bar{\varepsilon}_s + \bar{D}_s$, by applying the control law (26) and the adaptive law (28), all the signals in the slave subsystem are bounded with $e_s \rightarrow 0$ as $t \rightarrow \infty$, and the slave subsystem is asymptotically stable.

Proof: Define the Lyapunov function V_s as:

$$V_s = \frac{1}{2}s_s^2 + \frac{1}{2\Gamma_s}\tilde{W}_s^T\tilde{W}_s \quad (29)$$

where $\tilde{W}_s = W_s - \hat{W}_s$.

Subsequently, the derivative of V_s can be derived as:

$$\begin{aligned}\dot{V}_s &= s_s \dot{s}_s + \frac{1}{\Gamma_s}\tilde{W}_s^T\dot{\tilde{W}}_s \\ &= s_s(r_s \dot{e}_s + \sigma_s + u_s - F_e + d_s - \ddot{x}_{sd,o}) - \frac{1}{\Gamma_s}\tilde{W}_s^T\dot{\tilde{W}}_s\end{aligned}\quad (30)$$

Substitute (26) into (30), then (30) can be derived as:

$$\begin{aligned}\dot{V}_s &= s_s(\sigma_s - \hat{\sigma}_s - \nu_s s_s - \lambda_s \text{sgn}(s_s) + d_s) \\ &\quad - \frac{1}{\Gamma_s}\tilde{W}_s^T\dot{\tilde{W}}_s \\ &= -\nu_s s_s^2 + s_s(\varepsilon_s + d_s - \lambda_s \text{sgn}(s_s)) \\ &\quad + \tilde{W}_s^T(s_s h(\phi_s) - \frac{1}{\Gamma_s}\dot{\tilde{W}}_s)\end{aligned}\quad (31)$$

Substitute (27) into (31), then (31) can be derived as:

$$\dot{V}_s \leq -\nu_s s_s^2 + s_s(\varepsilon_s + d_s) - (\bar{\varepsilon}_s + \bar{D}_s) |s_s| \leq -\nu_s s_s^2 \quad (32)$$

According to the above analysis, $V_s \geq 0$ and $\dot{V}_s \leq 0$, which means V_s is bounded, and s_s and $\hat{\sigma}_s$ are bounded. Moreover, as $s_s \equiv 0$ when $\dot{V}_s \equiv 0$, the master subsystem is asymptotically stable (w.r.t. Lasalle invariance principle). Therefore, $s_s \rightarrow 0$ and $e_s, \dot{e}_s \rightarrow 0$ as $t \rightarrow \infty$. The proof is complete.

In order to obtain the control input $u_{s,i}$ for each slave robot, the coordinated distribution algorithm is designed based on the slave controller u_s in (26), and the distributed control input $u_{s,i}$ can be derived as:

$$[u_{s,1} \dots u_{s,i} \dots u_{s,n}] = L_s^* u_s + F_s^* \quad (33)$$

where

$$L_s^* = O^{-1} K_s^T (K_s O^{-1} K_s^T)^{-1}, \quad (34)$$

$$K_s = \left[\frac{dK_{o,1}^{-T}}{dx_{s,1}}, \dots, \frac{dK_{o,i}^{-T}}{dx_{s,i}}, \dots, \frac{dK_{o,n}^{-T}}{dx_{s,n}} \right], \quad (35)$$

O is the weight coefficient with regard to different target requirements, F_s^* is the internal force written as:

$$F_s^* = \left[\frac{dK_{o,1}^{-T}}{dx_{s,1}} - \frac{dK_{o,2}^{-T}}{dx_{s,2}} \frac{dK_{o,3}^{-T}}{dx_{s,3}} \dots \frac{dK_{o,n-1}^{-T}}{dx_{s,n-1}} - \frac{dK_{o,n}^{-T}}{dx_{s,n}} \right] f_s^*, \quad (36)$$

where f_s^* is the parameter selected with regard to different target requirements, and the internal force F_s^* satisfies

$K_s F_s^* = 0$, which means the internal force F_s^* will not affect the motion of target.

Therefore, the cooperative performance of slave robots to handle the target can be achieved with the distribution of $u_{s,i}$ for each slave robot via the coordinated distribution algorithm.

Based on the control design for multilateral teleoperation system, there are several remarks obtained as follows:

Remark 1. With the asymptotically stable of the master and slave subsystem guaranteed by *Theorem 1* and *Theorem 2*, and the non-power environment parameters' transmission of \hat{W}_e to avoid the passivity problem in the previous teleoperation control, the global stability of delayed nonlinear multilateral teleoperation system is guaranteed.

Remark 2. With the good control of $x_{s,o}(t) \rightarrow x_{sd,o}(t)$ via *Theorem 2*, and the good convergence of $x_{sd,o}(t) \rightarrow \frac{1}{n} \sum_{i=1}^n K_{o,i}(x_{m,i}(t-T(t)))$ by the stable $U_f(s)$, the good po-

sition tracking performance of $x_{s,o}(t) \rightarrow \frac{1}{n} \sum_{i=1}^n K_{o,i}(x_{m,i}(t-T(t)))$ is achieved.

Remark 3. With the good identification and reconstruction of environment dynamics via RBFNN algorithm, and the good control of $x_{m,i}(t) \rightarrow x_{md,i}(t)$ *Theorem 1*, the good force feedback performance of $\hat{F}_e \rightarrow F_e(t-T(t))$ is achieved.

Remark 4. With the coordinated distribution algorithm (33)-(36) to distribute $u_{s,i}$ with different target requirements for each slave robot, the good cooperative performance to handle the target is achieved.

4. EXPERIMENT

4.1 Experiment setup

The experiment for a typical multilateral teleoperation system with 2-master-2-slave robots is implemented on a real test platform, as shown in Fig.2, where two Phantom haptic devices with Joint 1 are used as master robots, and two slave robots with one-degree-of-freedom and the target are simulated in Matlab/Simulink environment, and the simulated parameters are selected as: $\alpha_{s,o} = 3$, $\beta_{s,o} = 1$. The environment force F_e is simulated with its parameters selected as $W_e^T = [0.4, 0.7, 0.5, 0.1, 0.5]$, $\phi_e = [\ddot{x}_{s,o}, \dot{x}_{s,o}, x_{s,o}]$, $\phi_{m,e} = [\ddot{x}_{md,o}, \dot{x}_{md,o}, x_{md,o}]$, the hidden nodes $y_e = y_{m,e} = 3$, $b_j = 3$, the matrices C_e and $C_{e,m}$ used in the identification and reconstruction of environment force are selected as $C_e = C_{e,m} = [-2, -1, 0, 1, 2]_{3 \times 5}$. The relationship (3) among the slave robots and target are selected as $x_{s,o} = \frac{1}{2}(x_{s,1} + x_{s,2})$. The external disturbances are selected as $d_{m,i} = d_s = 0.15 \sin t$. In order to implement a delayed communication channel, the $0.4 \pm 0.1s$ time-varying delays are added in the experiment.

The RBFNN-based sliding mode control design proposed in this paper is implemented in the experiment. The control law and the adaptive law for the i -th master robot are selected as (15) and (17), where $r_{m,i} = 10$, $\nu_{m,i} = 10$, $\Gamma_{m,i} = 800$ and $\lambda_{m,i} = 0.45$. The selected parameters in (11) are designed as $\alpha_{d,o} = 0$ and $\beta_{d,o} = 1.2$. The control law and the adaptive law for the slave subsystem

are selected as (26) and (28), where $r_s = 10$, $\nu_s = 10$, $\Gamma_s = 800$ and $\lambda_s = 0.45$. The τ_f in (22) is selected as $\tau_f = 0.03$. The coordinated distribution algorithm is selected with $O = 1$ and $f_s^* = 0$. In the $\hat{\sigma}_{m,i}$ and $\hat{\sigma}_s$, the hidden nodes are selected as $y = 5$, $b_{j,i} = b_{j,o} = 3$, and the matrices $C_{m,i}$ and $C_{s,o}$ including $c_{j,i}$ and $c_{j,o}$ used in the training of various uncertainties are selected as $C_{m,i} = C_{s,o} = [-2, -1, 0, 1, 2]_{3 \times 5}$, $b_{j,i} = b_{j,o} = 3$.

In the experiment, the slave robots are moved with the delayed human-enforced position signals $x_{m,i}$, and the target is moved by the slave robots with the desired trajectory $x_{sd,o}$. The experiment duration is 20s.

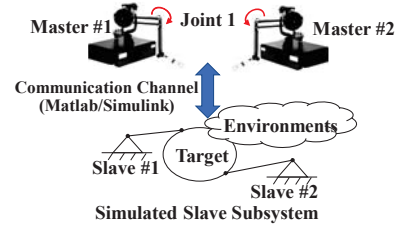


Fig. 2. Test platform.

4.2 Experiment results

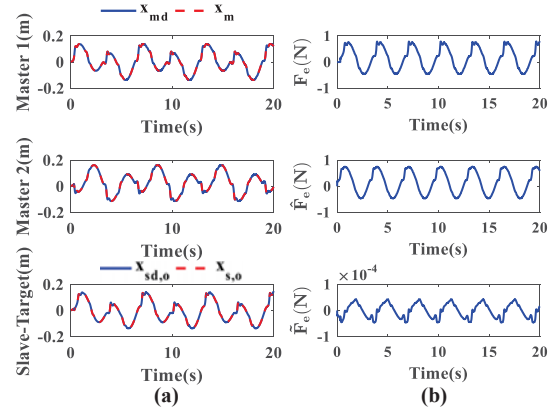


Fig. 3. The transparency performance with proposed control design. (a)Position tracking. (b)Force feedback.

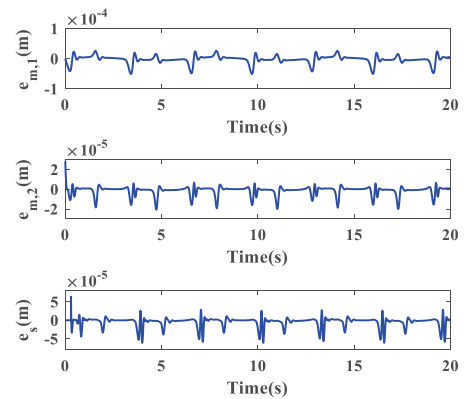


Fig. 4. The position tracking errors.

The experiment results are shown in Fig.3-Fig.5, where all the signals are bounded, which means the stability of system is guaranteed. With the proposed control design, the good identification and reconstruction of environment force F_e , the multilateral system has the good position

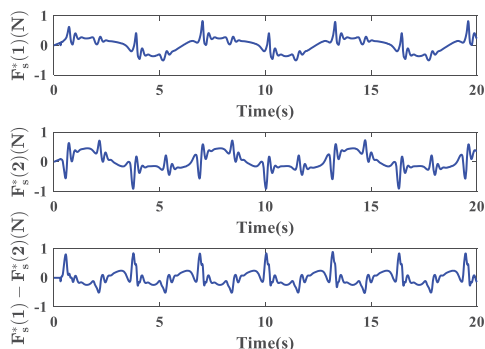


Fig. 5. The internal force of each slave robot.

tracking performance (show in Fig.3(a)) with small tracking errors (show in Fig.4) and good force feedback performance (show in Fig.3(b)). Moreover, Fig.5 shows the internal force of each slave robot, where $F_s^*(1) - F_s^*(2)$ has the same order of magnitude with $F_s^*(1)$ and $F_s^*(2)$, which means the slave robots can take the target to move under desired trajectory $x_{sd,o}$ (show in Fig.3(a)) with balanced internal force, and thus achieving the good cooperative performance.

5. CONCLUSION

In this paper, a novel multilateral control design for nonlinear teleoperation system is proposed to improve the capability of multiple robots to coordinate efficiently and precisely in the remote environments under time-varying delays and various uncertainties. The environment is modeled in a general form of force under RBFNN-based identification and reconstruction to avoid the passivity issue in the traditional teleoperation control and provide the human operators with good sensing of environments. The desired trajectory producers and RBFNN-based sliding mode controllers are designed separately to achieve the good tracking of master/slave robots, and the coordinated distribution algorithm is designed to obtain the control input $u_{s,i}$ for each slave robot. Therefore, the simultaneous stability, good transparency and cooperative performance of multilateral teleoperation system can be achieved theoretically. The real platform experiment is carried out on a 2-master-2-slave teleoperation system, and the results show the effectiveness of the proposed control design in the improvement of simultaneously achieving the stability, good transparency performance, and good cooperative performance for multiple master/slave robots under time-varying delays.

REFERENCES

Rebelo J, Schiele A, "Time Domain Passivity Controller for 4-channel Time-delay Bilateral Teleoperation," *IEEE Transactions on Haptics*, vol. 8, no. 1, pp. 79-89, 2015.

Z. Chen, Y. J. Pan and J. Gu, "Integrated Adaptive Robust Control for Multilateral Teleoperation Systems under Arbitrary Time Delays," *Int. J. Robust and Nonlinear Control*, vol. 26, no. 12, pp. 2708-2728, 2016.

X. Hou and R. Mahony, "Dynamic Kinesthetic Boundary for Haptic Teleoperation of VTOL Aerial Robots in Complex Environments," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 46, no. 5, pp.694-705, 2016.

Takhmar A, Polushin I G, Talasaz A, "Cooperative Teleoperation With Projection-Based Force Reflection for

MIS," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 4, pp.1411-1426, 2015.

M. Rank, Z. Shi, H. J. Mller and S. Hirche, "Predictive Communication Quality Control in Haptic Teleoperation With Time Delay and Packet Loss," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 4, pp.581-592, 2016.

F. Huang, W. Zhang, Z. Chen, J. Tang, W. Song and S. Zhu, "RBFNN-Based Adaptive Sliding Mode Control Design for Nonlinear Bilateral Teleoperation System Under Time-Varying Delays," *IEEE Access*, vol. 7, pp. 11905-11912, 2019.

Z. Chen, F. Huang, W. Chen, et. al., "RBFNN-based Adaptive Sliding Mode Control Design for Delayed Nonlinear Multilateral Tele-robotic System With Cooperative Manipulation," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 2, pp.1236-1247, 2020.

U. Farooq, J. Gu, M. El-Hawary, M. U. Asad and J. Luo, "An Extended State Convergence Architecture for Multilateral Teleoperation Systems," *IEEE Access*, vol. 5, pp. 2063-2079, 2017.

S. Sirouspour, "Modeling and control of cooperative teleoperation systems," *IEEE Transactions on Robotics*, vol. 21, no. 6, pp. 1220-1225, 2005.

Lo W T, Liu Y, et. al., "Cooperative teleoperation of a multirobot system with force reflection via Internet," *IEEE/ASME Transactions on Mechatronics*, vol. 9, no. 4, pp. 661-670, 2004.

Sun D, Naghdy F, Du H, "Neural Network-Based Passivity Control of Teleoperation System Under Time-Varying Delays," *IEEE Transactions on Cybernetics*, vol. 47, no. 7, pp. 1666-1680, 2017.

B. Khademan and K. Hashtrudi-Zaad, "Dual-user teleoperation systems: new multilateral shared control architecture and kinesthetic performance measures," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 5, pp. 895-906, 2012.

R. J. Anderson and M. W. Spong, "Bilateral Control of Teleoperators with Time Delay," *IEEE Transactions on Automatic Control*, vol. 34, no. 5, pp. 494-501, 1989.

G. Niemeyer and J. J. E. Slotine, "Stable Adaptive Teleoperation," *IEEE Journal of Oceanic Engineering*, vol. 16, no. 1, pp. 152-162, 1991.

B. Hannaford and J.-H. Ryu, "Time-domain passivity control of haptic interfaces," *IEEE Trans. Robot. and Automat.*, vol. 18, no. 1, pp. 426-434, 2002.

Y. Ye, Y.J. Pan, Y. Gupta and J. Ware, "A power based time domain passivity control for haptic interfaces," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 4, pp. 874-883, 2011.

T Kanno and Y Yokokohji "Multilateral teleoperation control over time-delayed computer networks using wave variables," *Haptics Symposium. IEEE*, pp. 125-131, 2012.

Z. Chen, F. Huang, C. Yang and B. Yao, "Adaptive Fuzzy Backstepping Control for Stable Nonlinear Bilateral Teleoperation Manipulators With Enhanced Transparency Performance," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 746-756, 2020.

B. Yao and M. Tomizuka, "Adaptive Robust Control of SISO Nonlinear Systems In a Semi-strict Feedback Form," *Automatica*, vol. 33, no. 5, pp. 893-900, 1997.