Teleoperation Control for Bimanual robots based on RBFNN and Wave Variable

Xingjian Wang, Chenguang Yang*, Junpei Zhong, Rongxin Cui, Min Wang

Abstract—**In this paper, a dual arm control method in a teleoperation system is introduced. For a bimanual robot, moving a common object precisely requires real-time cooperation between the two arms. In such conditions the force interaction including the internal forces applied on the object must be taken into account. Therefore the dynamics models for master device, slave robot and the object are first analysed. Because the presence of the uncertainties in the dynamics model of the remote robot, a neural network method is used for compensation in the slave part. In order to guarantee the stability of the teleoperation system, the wave variable approach is employed in the communication part. Then the controllers in both the master and the slave part are designed based on their dynamics models. Then the tracking convergence and system stability are proven by the Lyapunov function. Several simulation experiments are carried out to show the good performance of trajectory tracking and force reflection.**

Index Terms—**Bimanual Robot; Teleoperation Control; Wave Variable; RBF NN**

I. Introduction

In recent years, the need for human operators executing peculiar tasks in remote environments has gotten considerable attention, which has been applied in 3D game, telerobotic surgery, space and undersea exploration, search and rescue in hazadous environments and so on [1]. For this reason, the development of telemanipulation technologies has been experiencing growing interest during the past decade [2]. The objective of the teleoperation systems, in the main, is to control the slave robots to accomplish a task in the distance by master devices regardless of the presence of time variable time delay in the communication channel between the local and remote manipulators. In general, human operators can sense the force feedback and manipulate the telerobots in remote environments to accomplish more complicated tasks with bimanual manipulators. Compare with telemanipulator systems comprising a single haptic device in the master part and a single-arm manipulator in the slave part, a bimanual robot has outstanding capabilities in carrying and transporting things in the tele-environment. For example, in [2] a bimanual haptic telepresence system was used for dealing with explosive ordnance disposal in dangerous environments like unscrewing and excluding the detonator from the explosive, while the task was impossible to be accomplished by a single robot arm.

In the master part, two Geomagic® TouchX devices from SensAble Technologies Inc. are adopted. Every device could track motion by 6 rotational joints and provide force feedback by 3 joints equipped with motors. A 3-degrees-of-freedom (DOFs) gimbal joint stylus is installed at the end of every manipulator, which is to provide the orientation motion. As a simulated bimanual robot in the slave part, there are 7 revolute joints in each arm of Baxter [3], which make it easy to move in the 3-D space [3]. In order to grasp and handle the objects, a rotational gripper is installed at the end-effector of each arm [4]. The MATLAB Robotics Toolbox [5] is used for establishing kinematic models of the master joystick and for the simulation of the two arms of Baxter robot.

Due to the existence of uncertainties and time-delay in practical applications [6], research on controlling the uncertain robot system becomes very significant. The radial basis function (RBF) neural networks (NN) is a highly effective method and has been extensively used for control design of uncertain robot systems [7]. In [8], a controller is designed for dual-arm coordination of a humanoid robot based RBF NN control. RBF NN is investigated in [9] as a compensator to solve the non-linearities problem that a standard PD controller could not handle. In this paper, a NN controller based on PD control is applied to the two simulated bimanual robotic arms, which guarantees a more accurate trajectory tracking than the conventional PD controller.

Moreover, as we have known, the communication channels play significant roles in a teleoperation systems, and time delays in the channels may cause system unstable in the presence of force feedback [10]. A wave variable based control was proposed in [11] to handle the problem in the bilateral time-varying system. Based on this idea, a novel approach is presented for guaranteeing the stability of the time-varying delayed telepresence system based on PD control [12].

The reminder of the paper is organized as follows: Section II reports the problems and dynamic modeling in the telemanip-

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ulation system. To approximate the nonlinear dynamics in the slave part, RBF NN method is then introduced. To ensure the stability in the presence of time varying delays, wave variable method is finally introduced in this section. In Section III PD control on the master and slave is first discussed, and the nonlinear uncertainties of the model of the slave robot are then analysed. In order to compensate the uncertainties caused by the dynamics and time delay, RBF NN control is designed for the slave robot. Finally, the convergence of the tracking error and the stability of the teleoperation system with the time-varying delay are established. Several experiments are carried out in Section IV and conclusions are discussed in Section V.

II. Problem Formulation and Teleoperation System Modelling

A. *Modeling of the Teleoperation System*

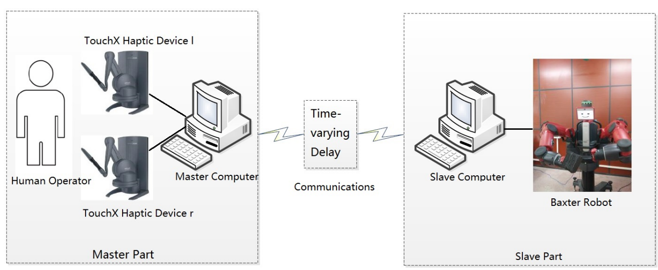

Fig. 1. The system framework

For both the local manipulators and the remote bimanual robot in the teleoperation system shown in Fig. 1, the positions and the orientations of their end-effectors can be calculated by their joint angles and angular velocities. Based on the forward kinematics of the local devices and the remote robot [13], the relations between task space and robot joint space can be represented as follows:

$$x_i = T_i(q_i), \dot{x}_i = \dot{T}_i(q_i) = J_i(q_i)\dot{q}_i \tag{1}$$

where $x_i \in \mathbb{R}^6$ represent the positions and orientations; $q_i, \dot{q}_i \in \mathbb{R}^{N_i}$ denote the angles and velocities of robotic joints respectively and N_i represent the degrees of freedom (DOF). T_i is a continuous function, and $J_i(q_i)$ are the Jacobian matrices. The subscript i stands for m and s, which denote the local master devices and remote slave arms of the bimanual robots, and the assumptions in [4] are taken into account in this paper.

As two TouchX haptic devices are used as the master devices, they can be represented by phase "l" and "r" respectively. In this paper we use the master devices TouchX l and r to control the left and right arms of the slave bimanual robot Baxter, respectively. Consider the dynamics of the TouchX l and the left arm of the Baxter robot in teleoperation system as follows, respectively:

$$\begin{aligned} M_{ml}(q_{ml}) + C_{ml}(q_{ml}, \dot{q}_{ml})\dot{q}_{ml} + &G_{ml}(q_{ml}) \\ &= J_{ml}^T(q_{ml})F_h - \tau_{ml} \end{aligned} \tag{2}$$

$$M_{sl}(q_{sl}) + C_{sl}(q_{sl}, \dot{q}_{sl})\dot{q}_{sl} + G_{sl}(q_{sl}) = \tau_{sl} - J_{sl}^T(q_{sl})F_{el} \tag{3}$$

where $M_{il}(q_{il}) \in \mathbb{R}^{N_i \times N_i}$, $C_{il}(q_{il}, \dot{q}_{il}) \in \mathbb{R}^{N_i \times N_i}$ and $G_{il}(q_{il}) \in \mathbb{R}^{N_i}$ represent the inertia matrices, Coriolis/centrifugal matrices and gravity vector, respectively. $\tau_{il} \in \mathbb{R}^{N_i}$ are the control input joint torques, F_h is the force vector exerted by the human operator and F_{el} is the force vector exerted at the left slave end-effector. $J_h(q_{il})$ are Jacobian matrices. The dynamics of the TouchX r and the right arm of the Baxter robot are similar to (2) and (3).

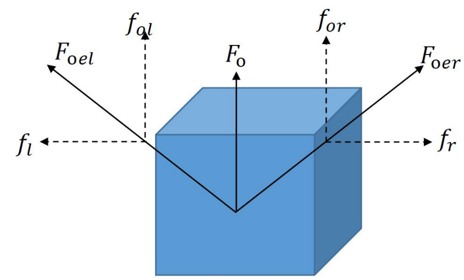

Fig. 2. Force decomposition of the common object

In the slave part, the dynamics of the object motion shown in Fig. 2 can be represented as:

$$M_o(x_o)\ddot{x}_o + C_o(x_o, \dot{x}_o)\dot{x}_o + G_o(x_o) = F_o \tag{4}$$

where $x_o, \dot{x}_o \in \mathbb{R}^{N_o}$ are the definitions of the positions/orientations and velocities of the object in the slave part. $M_o(x_o) \in \mathbb{R}^{N_o \times N_o}$, $C_o(x_o, \dot{x}_o) \in \mathbb{R}^{N_o \times N_o}$ and $G_o(x_o) \in \mathbb{R}^{N_o}$ are the inertia matrices, Coriolis/centrifugal matrices and gravity vector, respectively. $F_o \in \mathbb{R}^{N_o}$ is the force exerted to the object, while N_o is DOF of the object. Then the relationship between F_o and F_e can be represented as follows:

$$F_o = F_{el} + F_{er} = -F_{ol} - F_{or}, F_{oj} = f_j + f_{oj} \tag{5}$$

where F_{oj} are the contact force exerted on the object by the end-effectors of the slave robotic arms, f_{oj} devote the external forces deriving the motion of the object and f_j represent the internal forces canceling with each other and satisfying $f_l + f_r = 0_{[N_o]}$. The subscript j denotes l and r, which represent the left and right arm of the slave robot.

Based on [4], then we have

$$\tau_{sj} = M'_{sj}(q_{sj}) + C'_{sj}(q_{sj}, \dot{q}_{sj})\dot{q}_{sj} + G'_{sj}(q_{sj}) - J_{sj}^T(q_{sj})f_j \tag{6}$$

where $M'_{sj} = M_{sj} + M'_o$ and $M'_o = J_{sj}^T D_j M_o J_{sj}$, $C'_{sj} = C_{sj} + C'_o$ and $C'_o = J_{sj}^T D_j C_o J_{sj} + J_{sj}^T M'_o \dot{J}_{sj}$, $G'_{sj} = G_{sj} + G'_o$ and $G'_o = J_{sj}^T D_j G_o$, $D_j(t) \in \mathbb{R}^{N_o \times N_o}$ are object load distribution matrices satisfying $D_l(t) + D_r(t) = I_{N_o}$,.

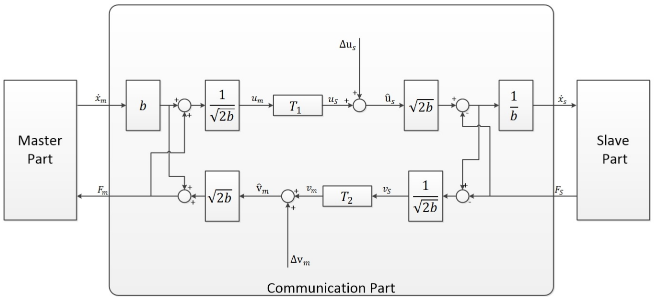

Fig. 3. Communication part with wave variables

B. RBF Neural Networks

RBF NN is used to approximate the dynamics of the robotic model with its local generalization network. It could greatly accelerate the learning speed, avoid the local minimum problem and improve the tracking accuracy of the robot especially for those with complicated structures and large numbers of DOFs [14]. The RBF NNs could be expressed as below:

$$\varphi_i = exp(-\frac{\|z-c_i\|^2}{\sigma_i^2}), i = 1, 2, ..., n \tag{7}$$

$$\hat{F}(z) = \hat{W}^T \varphi(z) \tag{8}$$

where $z \in \mathbb{R}^n$ is the input vector and n represents the DOF of the slave robot, which equals 7 for the left arm of the Baxter robot, $\hat{F}(z) \in \mathbb{R}^n$ is the output vector, $\varphi = [\varphi_1, \varphi_2, ..., \varphi_n]^T$ is the output vector of the hidden layer, $\hat{W} \in \mathbb{R}^{N\times n}$ is the weight matrix which connects the hidden layer and the output layer, and N represents the hidden nodes number, $c_i \in \mathbb{R}^n$ and $\sigma_i > 0$ are the center vector and width of the ith hidden node. From (7) the output of the hidden nodes in the RBF NNs is calculated by a radially symmetric function (e.g., Gaussian function).

In this paper, the RBF NNs are employed to approximate the uncertain nonlinear function $F(z)$ [15].

C. Wave Variable Method

The wave variable approach for the time-varying delayed communication is used in this section. In the communication channels, the time-varying delays T_1 and T_2 between the wave variables could be represented as follows

$$u_s(t) = u_m(t - T_1(t)) \tag{9}$$

$$v_m(t) = v_s(t - T_2(t)) \tag{10}$$

where u and v are the power variables transferred by the velocity $\dot{x}$ and the force F flowing into the communication channels.

And the relationship between the two kinds of variables is shown in Fig. 3, of which the representations are based on [15] .

To handle the time-varying delays in the communication of the teleoperation system, the wave correction method is employed [12], as shown in Fig. 3, which could be represented as follows

$$\Delta u_s(t) = \sqrt{2b}\lambda \left[x_{mf}(t) + x_{dh} - x_{sd}(t)\right] \tag{11}$$

$$\Delta v_m(t) = \sqrt{2b}\lambda \left[x_{sf}(t) + x_{dh} - x_{md}(t)\right] \tag{12}$$

where $\lambda > 0$ is designed for the convergence of position.

After applying the correction method, in the next section the controller design and the stability analysis of the teleopration system will be discussed.

III. Control Design

A. Controller Design in the slave part

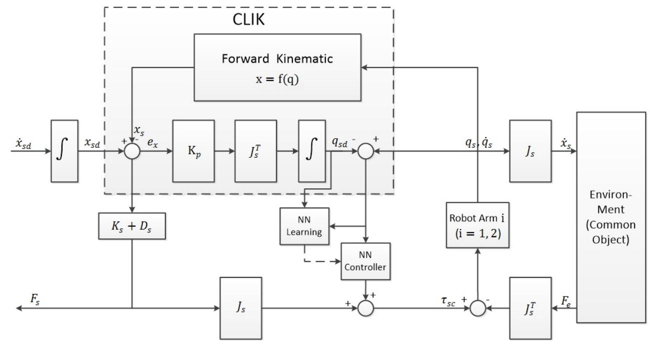

Fig. 4. Control method for Slave Bimanual robot

The controller in the master part are computed by the basic PD control algorithms represented in [15]. In this section, a control scheme is proposed using a torque control based on the nominal model and a NN controller to deal with the uncertainties.

The closed-loop inverse kinematics (CLIK) method shown in Fig. 4 is used for avoiding kinematic singularities and numerical drifts.

In the slave part, the PD controllers are also designed as follows

$$\tau_{scj} = -K_s e_{sj} - D_s \dot{e}_{sj} \tag{13}$$

where $e_{sj} = q_{sj} - q_{sjd}$ is the tracking error, $q_{sjd} \in \mathbb{R}^n$ is the desired joint angle served as the reference command for the local PD controller, $K \in \mathbb{R}^{n\times n}$ and $D \in \mathbb{R}^{n\times n}$ are the symmetric positive definite matrices for the joint angle and angular velocity gains.

Define the generalized tracking error

$$e_{vsj} = \dot{e}_{sj} + K_{s1} e_{sj} \tag{14}$$

where $K_{sj} = D_{sj}^{-1} K_{sj}$.

$$\tau_{sj} = -D_{sj} e_{vsj} \tag{15}$$

Define $q_{vj} = \dot{q}_{dj} - K_{sj} e_{sj}$, and the dynamics of the slave (6) can be rewritten as

$$M_{sj}\dot{e}_{vsj} + C_{sj}e_{vsj} + D_{sj}e_{vsj} = -J_{sj}^T f_j - G_{sj} + M_{sj}\dot{q}_{vj} - C_{sj}q_{vj} \tag{16}$$

and the uncertain nonlinear dynamics with the input z could be described by

$$F(z_j) = J_{sj}^T f_j - G_{sj} + M_{sj}\dot{q}_{vj} - C_s q_{vj} \tag{17}$$

For the uncertain models (17), the NN is of powerful function approximation ability, which could be used for the identification of the uncertainties.

Based on RBF NN method, (17) could be rewritten as follows

$$M_{sj}\dot{e}_{vsj} = -(C_{sj} + D_{sj})e_{vsj} + \hat{F}(z_j, W_j^*) + \eta \tag{18}$$

where $\eta = F(z_j) - \hat{F}(z_j, W_j^*)$ and W^* is the optimal weight matrix corresponding to $z_j \in X$.

According to the properties of the RBF NN, (18) could be rewritten as

$$M_{sj}\dot{e}_{vsj} = -(C_{sj} + D_{sj})e_{vsj} + W_j^{*T}\varphi(z_j) \tag{19}$$

With Lyapunov method it is easy to obtain the following update law

$$\dot{\hat{W}}_j = -Q_j^{-1}\varphi(z_j)e_{vsj}^T \tag{20}$$

where Q_j is a symmetric positive definite matrix. And the boundedness of RBF NN weights can be guaranteed by the persistence of excitation (PE) property [16].

The control torque is composed of two parts, as below

$$\tau_{sj} = -D_{sj}e_{vsj} + \hat{W}_j^T\varphi(z_j) \tag{21}$$

Then the closed-loop system dynamics of the slave robot can be written as

$$M_{sj}\dot{e}_{vsj} + C_{sj}e_{vsj} + D_{sj}e_{vsj} = F(z_j) - \hat{F}(z_j) \tag{22}$$

B. Theoretical Analysis

(I) Convergence of the tracking error

Proof: Choose a candidate of Lyapunov function as follows

$$V_1 = \frac{1}{2}e_{vs}^T M_s e_{vs} + \frac{1}{2}tr(\widetilde{W}^T Q\widetilde{W}) \tag{23}$$

Then, we have

$$\begin{aligned}\dot{V}_1 =& \frac{1}{2}e_{vs}^T\dot{M}_s e_{vs} + e_{vs}^T M_s\dot{e}_{vs} + tr(\widetilde{W}^T Q\dot{\hat{W}})\\ =& \frac{1}{2}e_{vs}^T\dot{M}_s e_{vs} - e_{vs}^T C_s e_{vs} - e_{vs}^T D_s e_{vs}\\ &- tr[\widetilde{W}^T(\varphi(z)e_{vs}^T - QQ^{-1}\varphi(z)e_{vs}^T)]\\ =& - e_{vs}^T D_s e_{vs} < 0\end{aligned} \tag{24}$$

such that we see $\dot{V}_1$ is strictly negative definite. According to [17], $e_{vs} \in L_2 \bigcap L_\infty$, $\dot{e}_{vs} \in L_\infty$, thus when $t \to \infty$, e_{vs} converges to zero asymptotically. And e_s and $\dot{e}_s$ converge to zero asymptotically with detailed analysis in [13].

(II) Stability of the teleoperation system

The proper selection of R_{vm} and R_{vs} that satisfy

$$\lambda_m(R_{vm}(t)) \geqslant \left(|\hat{v}_m|^2 - (1-\dot{T}_2)|v_m|^2\right)/2|\dot{x}_{md}|^2 \tag{25}$$

$$\lambda_m(R_{vs}(t)) \geqslant \left(|\hat{u}_s|^2 - (1-\dot{T}_1)|u_s|^2\right)/2|\dot{x}_{sd}|^2 \tag{26}$$

could guarantee the stability of the overall teleoperation system.

Proof: We choose another Lyapunov function candidate as below

$$V = V_c + V_w \tag{27}$$

where

$$V_w = \frac{1}{2}\int_{t-T_1}^{t} u_m^T u_m d\sigma + \frac{1}{2}\int_{t-T_2}^{t} v_s^T v_s d\sigma \tag{28}$$

$$\begin{aligned}V_c =& \frac{1}{2}\dot{q}_m^T M_m\dot{q}_m + \frac{1}{2}e_m^T K_m e_m + \frac{1}{2}e_{vs}^T M_s e_{vs}\\ &+ \frac{1}{2}tr(\widetilde{W}^T Q\widetilde{W})\end{aligned} \tag{29}$$

According to [12], we have

$$\begin{aligned}\dot{V}_w =& \frac{1}{2}(\dot{T}_1|u_s|^2 + |\delta u_s|^2 + 2u_s^T\delta u_s + \dot{T}_2|v_m|^2\\ &+ |\delta v_m|^2 + 2v_m^T\delta v_m)\end{aligned} \tag{30}$$

Considering (25) and (26), we have

$$\dot{V}_w \leqslant -\dot{x}_{md}^T R_{vm}'\dot{x}_{md} - \dot{x}_{sd}^T R_{vs}'\dot{x}_{sd} \tag{31}$$

where $R_{vm}' = R_{vm} - \lambda(R_{vm})I$ and $R_{vs}' = R_{vs} - \lambda(R_{vs})I$.

And according to (29), then we have

$$\dot{V}_c = \dot{x}_m^T F_h - \dot{x}_s^T F_e - \dot{q}_m^T D_m\dot{q}_m + \dot{V}_1 \tag{32}$$

As for the controllers on both the master and the slave sides, assume that the operator and the environment are passive [12], finally we could obtain

$$\begin{aligned}V(t) - V(0) \leqslant& \int_0^t (\dot{x}_m^T F_h - \dot{x}_s^T F_e)\\ &- \int_0^t \left(\dot{x}_{md}^T R_{vm}'\dot{x}_{md} + \dot{x}_{sd}^T R_{vs}'\dot{x}_{sd}\right) d\sigma\\ &+ \int_0^t \left(\dot{V}_1 - \dot{q}_m^T D_m\dot{q}_m\right) d\sigma\end{aligned} \tag{33}$$

which guarantees boundedness of V under the condition of passivity of the teleoperation system.

IV. Experimental Studies

The experimental platform is established including the master device and slave robot. Two haptic devices TouchX joysticks are employed as the master and a simulated bimanual Baxter robot is employed as the slave. The two joysticks of TouchX are first manipulated by a human operator, then the real-time positions are transferred to the two arms of simulated bimanual robot through the communication channel, respectively. The two simulated arms are controlled to grasp a common object cooperatively. Then the interaction force between the bimanual robot and the object, measured by the Simulink tool, are sent back to master part through communication and felt by the human operator finally. The structure of the teleoperation system is presented in Fig. 5 and the experiment platform is set up shown in Fig. 6.

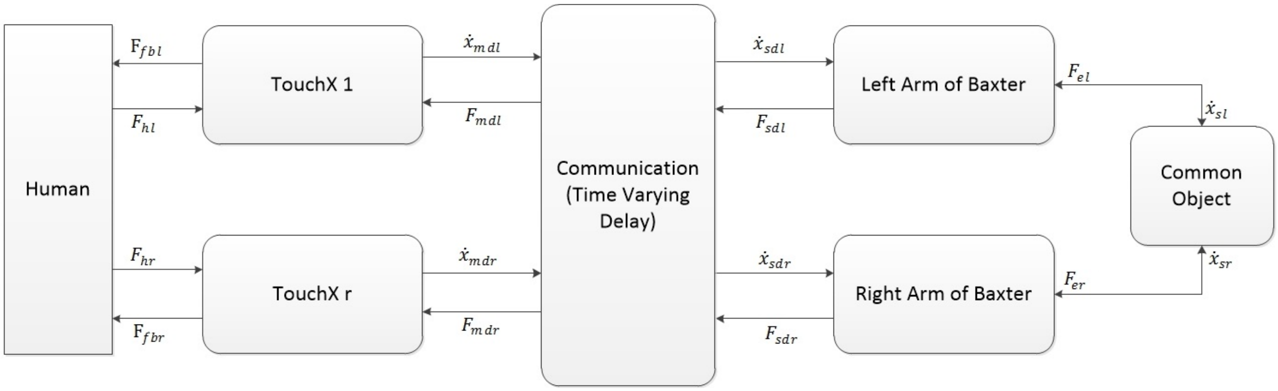

Fig. 5. Teleoperation control using the wave correction scheme with global neural controllers

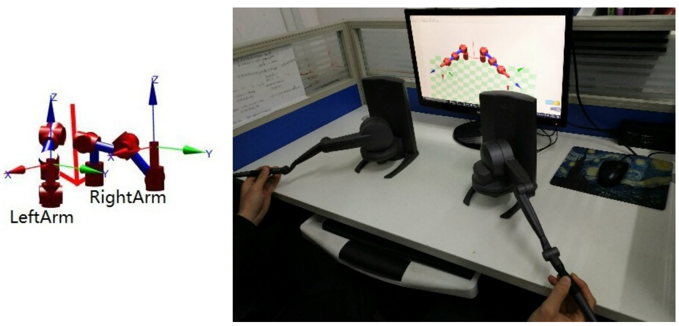

Fig. 6. Left: Simulated bimanual robot in the slave part. Right: Experiment platform of the teleoperation system (photo taken at South China University of Technology).

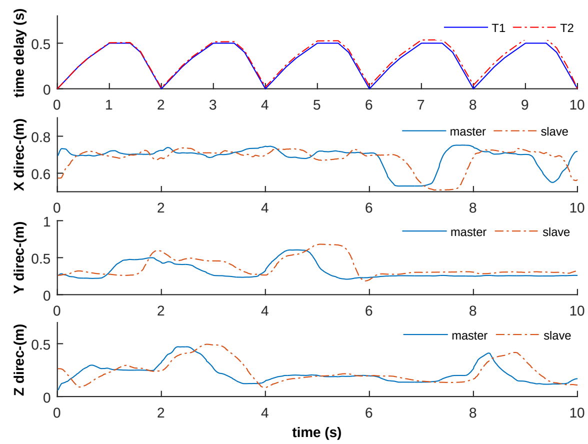

Fig. 7. Trajectory of the master device and the slave in the left part with time-varying delayed communication, using RBF NN and wave variable technique.

A. Trajectory tracking performance

In this part, the two arms of simulated Baxter robot track desired trajectories in the presence of the time-varying delays. The time-delay and the trajectories of master and slave in the left part and the right part are shown in Figs. 7 and 8, respectively, which demonstrate the good tracking performance in this teleoperation system.

B. Force feedback tracking performance

In this part, the two haptic devices in the master part receive the force feedback from the remote part, and the teleoperation system keeps stable because of the wave variable approach in the communications. The force reflection to the human operator in Fig. 5 are calculated by $F_{fbj} = K_{fb}(x_{mj} - x_{sj})$. The force feedback in the left part and right part of the teleoperation system are shown in Fig. 9 and 10, respectively, which demonstrate good performance in stability and force feedback. Based on the dynamics models of the robots, the control parameters are given as $D_{ij} = 50$ N-s/m, $K_{mj} = 1000$ N/m, $K_{sj} = 100$ N/m, $R_{vj} = b = 180$ N-s/m, and $\lambda = 100$.

And for controllers in the slave part, NN weight norm is depicted as shown in Fig. 11.

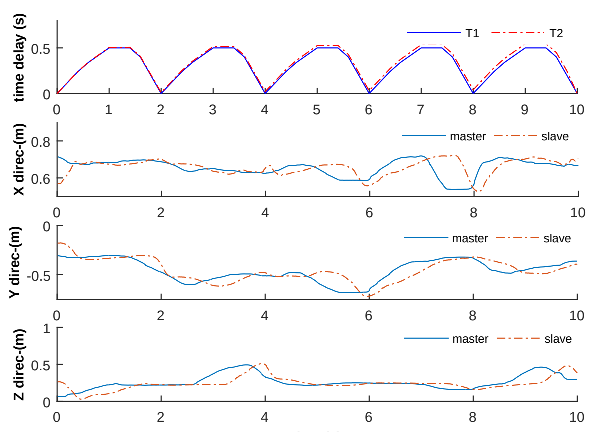

Fig. 8. Trajectory of the master device and the slave in the right part with time-varying delayed communication, using RBF NN and wave variable technique.

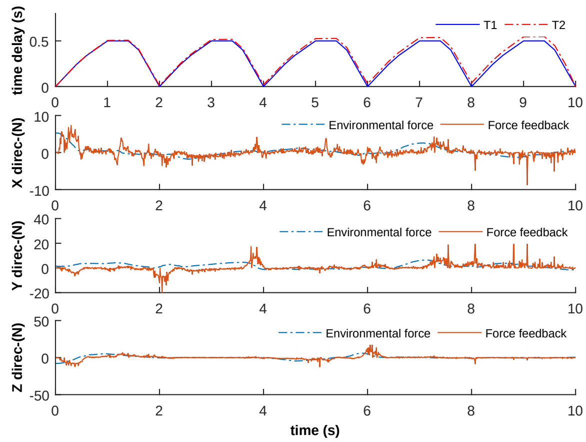

Fig. 9. Force reflection in the left part to the environmental force from time-varying delayed communication.

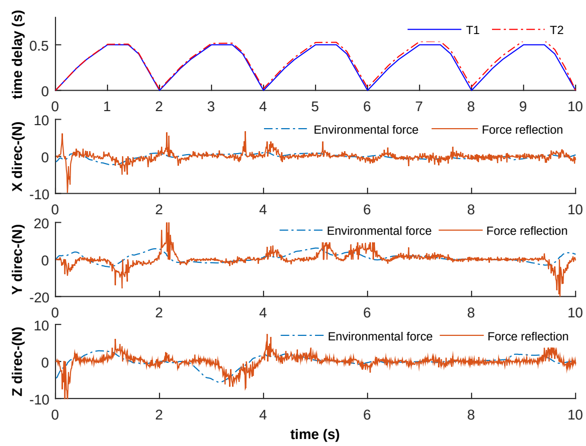

Fig. 10. Force reflection in the right part to the environmental force from time-varying delayed communication.

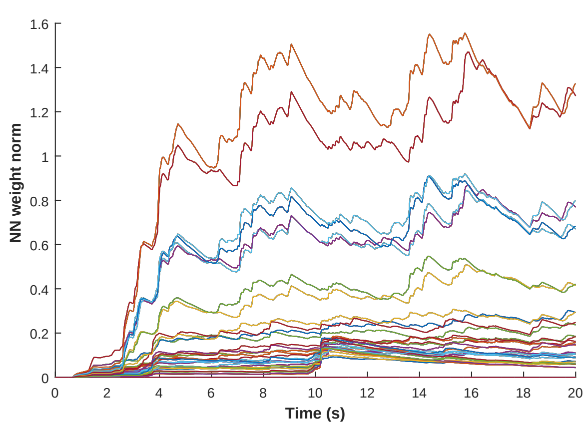

Fig. 11. NN weight norm.

V. Conclusion

In this paper, a novel teleoperation technique for the simulated bimanual robot based on RBF NN and wave variable has been presented, which is conducted in the presence of time-varying delay and uncertain dynamics of both slave robots and the manipulated object. The tracking convergence and stability in the teleoperation system have been proofed based on Lyapunuv functions. Finally several experiments are carried out to validate the proposed method.

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