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Robust Coordination Control Interface for Networked Based Telerobotic System

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Abstract— **In this paper, we propose coordination control interface for transparent networked telerobotic system under delay and bounded uncertainty. The coordination control input interface for the master manipulator combines delayed position-velocity signals with the delayed estimated impedance properties of the interaction between slave and remote environment. The delayed position-velocity signals of the master manipulator are used to develop input interaction interface for slave manipulator. The master and slave input interface design also employs with the local position and velocity signal of the master and slave manipulator. Both master and slave input interface uses adaptive terms locally to estimate the interaction properties between human and master manipulator and between slave and remote environment. To deal with the uncertainty associated with the unmodeled dynamic and external input disturbance, robust term combined locally with adaptive control term. Using Lyapunov analysis, the stability condition is derived in the presence of delays. Finally, evaluation results are presented to demonstrate the effectiveness of the proposed input interface for real-time applications.**

I. Introduction

The purpose of designing a networked based telerobotic system is to transfer human operators manipulation capability to an remotely located slave system. Most recent results in this direction can be found in [1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 28, 29, 30]. The results presented in [1, 3, 4, 7, 8, 9, 13, 14, 15, 20, 21, 25, 27, 28, 29, 30] can only ensure that the slave reproduces the motion of the master system. On the other hand, hybrid algorithms reported in [2, 5, 6, 11, 16, 17 18, 19, 22, 23, 24] can synchronize motion between master and slave system and human operator can feel the remote interaction force between slave and environment.

It can be noticed from existing hybrid control interface designs that they reflects either measured interaction forces between slave and environment or slaves input toque to the human operators hand. On the other hand, the input interaction forces in existing methods are assumed to be known to guarantee stability and tracking property of motion and interaction force which may be difficult to satisfy as most advanced manipulator does not equip with force sensor. Moreover, the exiting design and analysis does not consider uncertainty associated with the unmodeled dynamic and external disturbance.

In this work, we introduce robust coordination control interface for transparent networked telerobotic system under delay and bounded uncertainty. The input interface for master is designed by combining delayed position-velocity signals of the slave with the estimated impedance properties of the interaction between slave and environment. The delayed position-velocity signals of the master manipulator are used to develop input interaction interface for slave manipulator. The local position and velocity signals also includes with the input interface of the master and slave manipulator in order to improve the motion tracking performance. The reflected interaction properties to human operators hand improve the force transparency between human and environment. Adaptive term integrates with both master and slave input interface to learn and adapt uncertainty associated with interaction properties between human and master and between slave and remote environment. Robust and adaptive control term incorporates locally with the input interface of the master and slave manipulator to learn and compensate uncertainty associated with the gravity, unmodeled dynamic and external disturbance. The convergence analysis is shown by using Lyapunov method under asymmetrical time varying delay. The proposed design does not require measurement of the input interaction forces between human and master and between slave and remote environment. The control input interface strategy introduced in this work does not require exact knowledge of the unmodeled dynamic and external disturbance. The stability analysis is established without using LMI conditions. Finally, evaluation results are presented to demonstrate the effectiveness of the proposed design for real-world applications.

The rest of the paper is organized as follows: Section II presents model and properties of the shared autonomous system. Section II develops control input interface algorithm. Convergence analysis is also given in section II. Section III shows evaluation results of the proposed method. Conclusion is given in section IV.

II. Model Dynamics, Algorithm Design and Convergence Analysis

The motion dynamic for n-DOF master and slave manipulator with human and environment input interaction forces can be modeled by the following equation

$$\begin{aligned} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + G_m(x_m) &= T_m \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s + G_s(x_s) &= T_s \quad (1) \end{aligned}$$

where $T_m = (\tau_m + \eta_h + d_m)$, $T_s = (\tau_s + \eta_e + d_m)$, $\eta_h = J_m^T F_h$, $\eta_e = J_m^T F_e$, η_h and η_e denotes the torque applied to the master and slave by human operator and remote environment, d_m and d_s defines uncertainty associated with

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unmodeled dynamic and other external input disturbance to the master and slave manipulator, J_m and J_e defines the Jacobian matrices for the master and slave manipulator, F_h and F_e presents exerted forces by operator and environment to the master and slave manipulator, $\ddot{x}_m$, $\dot{x}_m$, x_m and $\ddot{x}_s$, $\dot{x}_s$, x_s are the joint acceleration, velocity and position, $M_m(x_m)$ and $M_s(x_s)$ are the symmetric and uniformly positive definite inertia matrices, $C_m(x_m, \dot{x}_m)\dot{x}_m$ and $C_s(x_s, \dot{x}_s)\dot{x}_s$ are the coriolis and centrifugal vectors, $G_m(x_m)$ and $G_s(x_s)$ are the gravity vectors, m and s defines the master and slave system, respectively.

In our convergence analysis, the following dynamical property of the master and slave manipulator will be used [10]. $P1$: The matrices $\dot{M}_m(x_m) - 2C_m(x_m, \dot{x_m})$ and $\dot{M}_s(x_s) - 2C_s(x_s, \dot{x_s})$ are skew symmetric. $P2$: The matrices $M_m(x_m)$ and $M_s(x_s)$ are symmetric, bounded and positive definite. $P3$: There exists positive constant parameters k_1 and k_2 such that the gravity vectors are bounded as $\|G_m(x_m)\| \leq k_1$ and $\|G_s(x_s)\| \leq k_2$. $P4$: The matrices $C_m(x_m, \dot{x}_m)$ and $C_s(x_s, \dot{x}_s)$ are bounded as $\|C_m(x_m, \dot{x}_m)\| \leq c_m\|\dot{x}_m\|$ and $\|C_s(x_s, \dot{x}_s)\| \leq c_s\|\dot{x}_s\|$ with $c_m > 0$ and $c_s > 0$. It is also assumed that A_1 : The unmodeled dynamic and input external disturbance $d_m(t)$ and $d_s(t)$ and their time derivatives are continuous and bounded.

It is assumed in this work that the force sensors with master and slave haptic manipulator are not available for the measurement of the input interaction forces. In fact, most advanced manipulator does not have force sensor to reduce the size and overall cost of the system. The input interaction forces between human and master and between slave and environment can be estimated by the following constant-spring-damper model

$$\eta_h = a_h + b_m\dot{x}_m + a_m x_m, \eta_e = a_e + b_s\dot{x}_s + a_s x_s \quad (2)$$

where $a_m \in \Re^{n\times n}$, $a_s \in \Re^{n\times n}$, $b_m \in \Re^{n\times n}$, $b_s \in \Re^{n\times n}$, $a_h \in \Re^{n\times 1}$ and $a_e \in \Re^{n\times 1}$. Note that the input interaction matrices a_m, a_s, b_m and b_s are assumed to be bounded as $\|a_m\| \leq \gamma_m$, $\|a_s\| \leq \gamma_s$, $\|b_m\| \leq \zeta_m$ and $\|b_s\| \leq \zeta_s$ with $\gamma_m > 0$, $\gamma_s > 0$, $\zeta_m > 0$ and $\zeta_s > 0$. The vectors a_e and a_h are also bounded as $\|a_e\| \leq \gamma_e$ and $\|a_h\| \leq \gamma_h$ with $\gamma_h > 0$ and $\gamma_e > 0$. The interaction parameters in models (2)-(4) are unknown and estimated by using adaptive control algorithm. The estimated interaction parameters reflect back to the operators hand by master manipulator to improve the transparency of the bilateral shared autonomous system. The Jacobian matrices J_m and J_s for the master and slave manipulator are assumed to be nonsingular and bounded. Then, we design the following control input interaction interface for the bilateral shared autonomous system (1)

$$\begin{aligned}\tau_m &= -\pi_d\left(\dot{x}_m - \dot{x}_s(t-\mathcal{R}_{ds}(t))\right) + \hat{\theta}_{gm} sgn(\dot{x}_m) - \\ &\quad \pi_p\left(x_m - x_s(t-\mathcal{R}_{ds}(t))\right) - \hat{\zeta}_{ef}(t-\mathcal{R}_{ds}(t)) \\ &\quad -\hat{\eta}_h \\ \tau_s &= \omega_d\left(\dot{x}_m(t-\mathcal{R}_{dm}(t)) - \dot{x}_s\right) - \omega_p x_s + \hat{\theta}_{gs} \\ &\quad sgn(\dot{x}_s) + \omega_p x_m(t-\mathcal{R}_{dm}(t)) - \hat{\eta}_e \end{aligned} \quad (3)$$

where $\hat{\zeta}_{ef}(t-\mathcal{R}_{ds}(t)) = J_m^T\kappa_h\hat{\theta}_{re}(t-\mathcal{R}_{ds}(t))$, $\hat{\eta}_e = J_s^T\kappa_e\hat{\theta}_{re}$, $\hat{\eta}_h = J_m^T\kappa_h\hat{\theta}_{lh}$, $\pi_p > 0$, $\pi_d > 0$, $\omega_p > 0$, $\omega_d > 0$, $\kappa_h = [x_m, \dot{x}_m, I]$, $\kappa_e = [x_s, \dot{x}_s, I]$, $\theta_{re} = [\gamma_s, \zeta_s, \gamma_e]^T$ and $\theta_{lh} = [\gamma_m, \zeta_m, \gamma_h]^T$, $\hat{\theta}_{gm}$and $\hat{\theta}_{gs}$ are the estimate of the parameters $\|d_m - G_m(x_m)\| \leq \theta_{gm}$ and $\|d_s - G_s(x_s)\| \leq \theta_{gs}$ where $\theta_{gm} = (k_1 + f_m)$ and $\theta_{gs} = (k_2 + f_s)$ according to property $P3$ and assumption A_1 as $\|d_m\| \leq f_m$, $\|d_s\| \leq f_s$ with $f_m > 0$ and $f_s > 0$. $\hat{\theta}_{re}$ and $\hat{\theta}_{lh}$ are the estimates of θ_{re} and θ_{lh}. The delays in forward $\mathcal{R}_{dm}(t)$ and backward path $\mathcal{R}_{ds}(t)$ are asymmetrical and time varying as $\mathcal{R}_{dm}(t) \neq \mathcal{R}_{ds}(t)$ Using (1), (3), the closed loop systems can be formulated as follows

$$\begin{aligned}\ddot{x}_m &= M_m^{-1}(x_m)[\pi_d\dot{x}_s(t-\mathcal{R}_{ds}(t)) - \pi_p x_m - \pi_d\dot{x}_m \\ &\quad -C_m(x_m, \dot{x}_m)\dot{x}_m + \tilde{\theta}_{gm} sgn(\dot{x}_m) + \tilde{\eta}_h - \\ &\quad \hat{\zeta}_{ef}(t-\mathcal{R}_{ds}(t)) + \pi_p x_s(t-\mathcal{R}_{ds}(t))] \\ \ddot{x}_s &= M_s^{-1}(q_s)[\omega_d\dot{x}_m(t-\mathcal{R}_{dm}(t)) - C_s(x_s, \dot{x}_s)\dot{x}_s + \\ &\quad \tilde{\theta}_{gs} sgn(\dot{x}_s) + \omega_p x_m(t-\mathcal{R}_{dm}(t)) - \omega_d\dot{x}_s \\ &\quad -\omega_p x_s + \tilde{\eta}_e] \end{aligned} \quad (4)$$

where $\tilde{\eta}_e = J_s^T\kappa_e\tilde{\theta}_{re}$, $\tilde{\eta}_h = J_m^T\kappa_h\tilde{\theta}_{lh}$, $\tilde{\theta}_{re} = \left(\theta_{re} - \hat{\theta}_{re}\right)$, $\tilde{\theta}_{lh} = \left(\theta_{lh} - \hat{\theta}_{lh}\right)$, $\tilde{\theta}_{gm} = \left(\theta_{gm} - \hat{\theta}_{gm}\right)$, $\tilde{\theta}_{gs} = \left(\theta_{gs} - \hat{\theta}_{gs}\right)$, $\dot{\hat{\theta}}_{gm} = -\Gamma_{gm} sgn^T(\dot{x}_m)\dot{x}_m$, $\dot{\hat{\theta}}_{gs} = -\alpha_s sgn^T(\dot{x}_s)\dot{x}_s$, $\dot{\hat{\theta}}_{lh} = \Gamma_{lh}\kappa_h^T J_m\dot{x}_m$, $\dot{\hat{\theta}}_{re} = \alpha_e\kappa_e^T J_s\dot{x}_s$, $\alpha_s = \Gamma_{gs}\beta_s$, $\alpha_e = \Gamma_{re}\beta_s$, $\Gamma_{gs} > 0$, $\Gamma_{gm} > 0$, $\Gamma_{lh} \in \Re^{n\times n}$ and $\Gamma_{re} \in \Re^{n\times n}$ are positive definite constant diagonal matrices, Then, in view of Lyapunov argument, properties $P1$ to $P4$, assumption A_1 and Barbalat's lemma [31], we can state the following Theorem.

Theorem 1 : *Consider the closed loop telerobotic systems (4) with properties* $(P1 - P4)$ *and assumption* A_1 *under control input interaction interface (3). Then, there exists positive constants* $\pi_p > 0$, $\pi_d > 0$, $\omega_p > 0$, $\omega_d > 0$, $\Gamma_{gm} > 0$, $\Gamma_{gs} > 0$ *and positive definite constant diagonal matrices* Γ_{re} *and* Γ_{lh} *such that the position, velocity and the input interaction forces are bounded and their bounds asymptotically converges to zero.*

Remark 1: To ensure the learning estimates $\dot{\hat{\theta}}_{gm}$, $\dot{\hat{\theta}}_{lh}$, $\dot{\hat{\theta}}_{gs}$ and $\dot{\hat{\theta}}_{re}$ remain bounded without discontinuity property, the projection mechanism can be employed as $\dot{\hat{\theta}}_{gm} = Proj\left(\theta_{gm}, -\Gamma_{gm} sgn^T(\dot{x}_m)\dot{x}_m\right)$, $\dot{\hat{\theta}}_{gs} = Proj\left(\theta_{gs}, -\alpha_s sgn^T(\dot{x}_s)\dot{x}_s\right)$, $\dot{\hat{\theta}}_{lh} = Proj\left(\theta_{lh}, -\Gamma_{lh}\kappa_h^T J_m\dot{x}_m\right)$, $\dot{\hat{\theta}}_{re} = Proj\left(\theta_{re}, -\alpha_e\kappa_e^T J_s\dot{x}_s\right)$ [32]. This implies that for $\hat{\theta}_k(0) \in \Omega_k$ with $\hat{\theta}_k \in \Omega_k = \{\hat{\theta}_k \mid a_k \leq \hat{\theta}_k \leq b_k\}$, $k = gm, gs, lh, re$, $a_k > 0$ and $b_k > 0$, then $\hat{\theta}_k(t) \in \Omega_{\delta_k}$ with $\Omega_{\delta_k} = \{\hat{\theta}_k \mid a_k - \delta_k \leq \hat{\theta}_k \leq b_k + \delta_k\}$ and $\delta_k > 0$ $\forall t \geq 0$. Since $\hat{\theta}_k \in \Omega_{\delta_k}$, then it is also possible to guarantee the boundedness of parameter estimation errors $\tilde{\theta}_k$.

III. Evaluation Results

In this section, we examine the effectiveness of the proposed control input interface on a bilateral shared au-

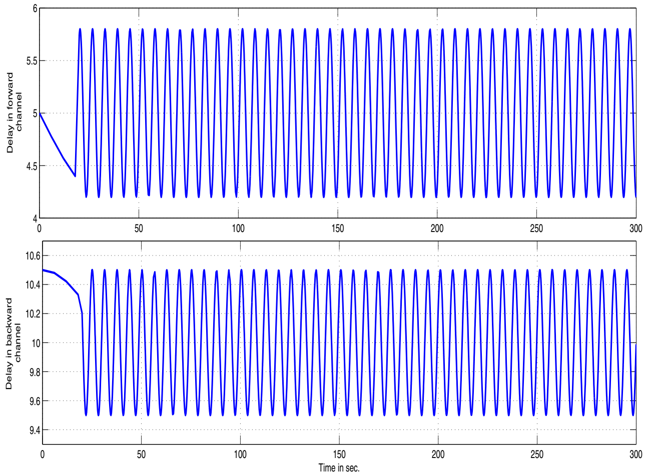

Fig. 1. Asymmetrical forward and backward delays $\mathcal{R}_{dm}(t)$ and $\mathcal{R}_{ds}(t)$ in sec.

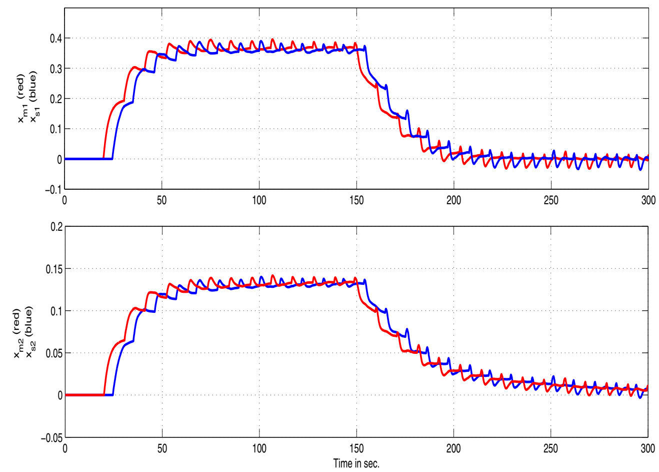

Fig. 2. Time history of the position of the master and slave manipulator x_{m1}, x_{s1}, x_{m2} and x_{s2} in radians.

tonomous system. In our evaluation, the local and remote platforms are equipped with 2-DOF master manipulator and 2-DOF slave manipulator. The master and slave manipulator is connected by open internet communication channel. The motion dynamic of 2-DOF master and 2-DOF slave manipulator interacting with human and environment can be modeled as follows

$$\begin{aligned} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + G_m(x_m) &= T_m \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{q}_s)\dot{x}_s + G_s(x_s) &= T_s \end{aligned} \tag{5}$$

where $M_m(x_m) = \begin{bmatrix} m_{11m} & m_{12m} \\ m_{21m} & m_{22m} \end{bmatrix}$, $M_s(x_s) = \begin{bmatrix} m_{11s} & m_{12s} \\ m_{21s} & m_{22s} \end{bmatrix}$, $C_m(x_m,\dot{x}_m) = \begin{bmatrix} C_{11m} & C_{12m} \\ C_{21m} & C_{22m} \end{bmatrix}$, $C_s(x_s,\dot{x}_s) = \begin{bmatrix} C_{11s} & C_{12s} \\ C_{21s} & C_{22s} \end{bmatrix}$, $G_m(x_m) = \begin{bmatrix} G_{m1} \\ G_{m2} \end{bmatrix}$, $G_s(x_s) = \begin{bmatrix} G_{s1} \\ G_{s2} \end{bmatrix}$, $T_m = \begin{bmatrix} T_{m1} \\ T_{m2} \end{bmatrix}$, $T_s = \begin{bmatrix} G_{s1} \\ G_{s2} \end{bmatrix}$, $\tau_m = \begin{bmatrix} \tau_{m1} \\ \tau_{m2} \end{bmatrix}$, $\tau_s = \begin{bmatrix} \tau_{s1} \\ \tau_{s2} \end{bmatrix}$, $\eta_h = \begin{bmatrix} \eta_{h1} \\ \eta_{h2} \end{bmatrix}$, $\eta_e = \begin{bmatrix} \eta_{e1} \\ \eta_{e2} \end{bmatrix}$, $d_m = \begin{bmatrix} d_{m1} \\ d_{m2} \end{bmatrix}$, $d_s = \begin{bmatrix} d_{s1} \\ d_{s2} \end{bmatrix}$ with $m_{11m} = m_{2m}l_m^2 + (m_{1m}+m_{2m})l_m^2 + 2m_{2m}l_m^2\cos(x_{m2})$, $m_{12m} = m_{2m}l_m^2 + m_{2m}l_m^2\cos(x_{m2})$, $m_{21m} = m_{2m}l_m^2 + 2m_{2m}l_m^2\cos(x_{m2})$, $m_{22m} = m_{2m}l_m^2$, $C_{11m} = -\dot{x}_{m2}m_{2m}l_m^2\sin(x_{m2})$, $C_{12m} = -(\dot{x}_{m1}+\dot{x}_{m2})m_{2m}l_s^2\sin(x_{m2})$, $C_{21m} = \dot{x}_{m1}m_{2m}l_s^2\sin(x_{m2})$, $C_{22m} = 0$, $G_{m1} = gm_{2m}l_m\sin(x_{m1}+x_{m2}) + g(m_{1m}+m_{2m})l_m\sin(x_{m1})$, $G_{m2} = gm_{2m}l_m\sin(x_{m1}+x_{m2})$, $m_{11s} = m_{2s}l_s^2 + (m_{1s}+m_{2s})l_s^2 + 2m_{2s}l_s^2\cos(x_{s2})$, $m_{12s} = m_{2s}l_s^2 + m_{2s}l_s^2\cos(x_{s2})$, $m_{21s} = m_{2s}l_s^2 + 2m_{2s}l_s^2\cos(x_{s2})$, $m_{22s} = m_{2s}l_s^2$, $C_{11s} = -\dot{x}_{s2}m_{2s}l_s^2\sin(x_{s2})$, $C_{12s} = -(\dot{x}_{s1}+\dot{x}_{s2})m_{2s}l_s^2\sin(x_{s2})$, $C_{21s} = \dot{x}_{s1}m_{2s}l_s^2\sin(x_{s2})$, $C_{22s} = 0$, $G_{s1} = gm_{2s}l_s\sin(x_{s1}+x_{s2}) + g(m_{1s}+m_{2s})l_s\sin(x_{s1})$, $G_{s2} = gm_{2s}l_s\sin(x_{s1}+x_{s2})$, $l_{m1} = l_{m2} = l_m$, $l_{s1} = l_{s2} = l_s$, l_{m1} and l_{m2} are the length of the link 1 and link 2 for the master manipulator, l_{s1} and l_{s2} are the length of the link 1 and link 2 for the slave manipulator, m_{1m} and m_{2m} are the masses of the link 1 and link 2 for the master manipulator, m_{1s} and m_{2s} are the masses of the link 1 and link 2 for the slave manipulator. The model parameters for master and slave manipulators are chosen as $m_{1m} = m_{2m} = 7kg$, $m_{1s} = 5kg$, $m_{2s} = 5kg$, $l_{m1} = l_{s1} = 1m$, $l_{m2} = l_{s2} = 0.5m$ and $g = 9.82\frac{m}{s^2}$. The unmodeled dynamic and external input disturbances in T_m and T_s are chosen as $d_{m1} = d_{m2} = 10\sin t$ and $d_{s1} = d_{s2} = 10\cos t$. It is assumed in our design and evaluation that the input interaction forces with master, F_h, and slave, F_e, are not measurable. The control interface design parameters for our evaluation are chosen as $\pi_p = 400$, $\pi_d = 600$, $\omega_p = 700$, $\omega_d = 1000$, $\Gamma_{gm} = 5$, $\Gamma_{gs} = 5$,$\Gamma_{lh} = 30I_{3\times3}$, $\Gamma_{re} = 30I_{3\times3}$.

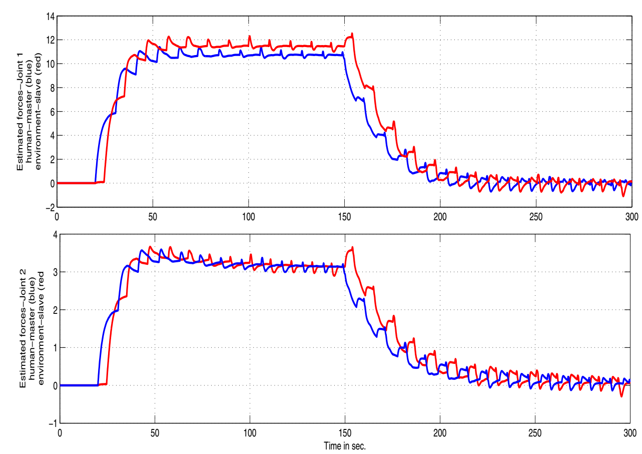

Fig. 3. Time history of the estimated input interaction forces between human and master, $\hat{\eta}_{h1}$ and $\hat{\eta}_{h2}$, and estimated interaction forces between slave and environment, $\hat{\eta}_{e1}$ and $\hat{\eta}_{e2}$, in Newton.

Let us now apply coordination input interaction interface

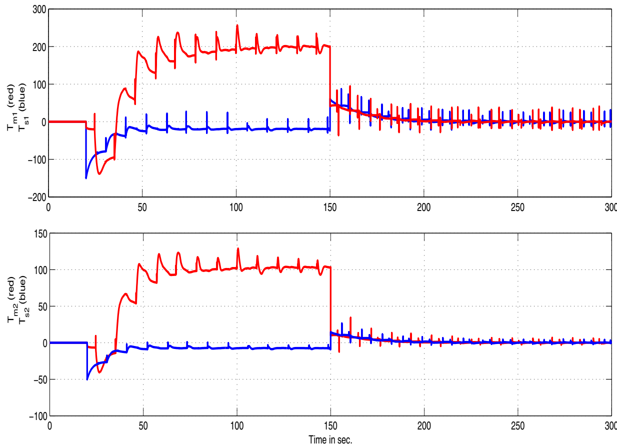

Fig. 4. The input torques for master and slave T_{m1}, T_{s1}, T_{m2} and T_{s2} in Newton-meter.

algorithm (3) for a scenario where the slave manipulator moves in the presence of very hard environment under asymmetrical delay and bounded uncertainty associated with unmodeled dynamic and external disturbance. Evaluation examines the effectiveness of the proposed interface by verifying the stability and tracking property of the motion of the master and slave manipulator and the input interaction forces to the master and slave manipulator. To examine that, the input interaction forces between human and master are estimated by model (2) as $\eta_{h1} = a_{h1} + b_{m1}\dot{x}_{m1} + a_{m1}x_{m1}$, $\eta_{h2} = a_{h2} + b_{m2}\dot{x}_{m2} + a_{m2}x_{m2}$ with $a_{m1} = 5$, $a_{m2} = 5$, $b_{m1} = 6$, $b_{m2} = 6$, $a_{h1} = 100$ and $a_{h2} = 100$. The input interaction forces between slave and very hard uncertain remote environment are modeled as $\eta_{e1} = a_{e1} + b_{s1}\dot{x}_{s1} + a_{s1}x_{s1}$ and $\eta_{e2} = a_{e2}+b_{s2}\dot{x}_{s2}+a_{s2}x_{s2}$ with $a_{e1} = 10$, $a_{e2} = 10$, $b_{s1} = 20$, $b_{s2} = 20$, $a_{s1} = 5000$ and $a_{s2} = 5000$. For our evaluation, asymmetrical data transmission delays over the open communication channel are chosen as shown in Fig. 1. Then, we apply algorithm (3) on the given bilateral shared autonomous system. The evaluation results are depicted in Figs. 2 to 4. Fig. 2 depicts the time history of the joint position tracking of the master and slave manipulator. Fig. 3 shows the estimated interaction forces profile between human operator and master and between slave and very hard environment. The input torques for master and slave manipulator are presented in Fig. 4. From Fig. 2, we can see that the slave manipulator can follow the movement of the master manipulator. In view of Fig. 3, we can also notice that the estimated input interaction forces between master and slave manipulator are equal to the estimated input interaction forces between slave and environment in the presence of asymmetrical delay and bounded uncertainty provided that the input interaction forces are not measurable.

IV. Conclusion

In this paper, we presented robust coordination control interface for networked based telerobotic systems under delay. Lyapunov method used to develop the stability and convergence property of the closed loop system. The proposed coordination control interface design is simple and easy to implement as it does not require exact knowledge of the manipulator dynamics and uncertainty associated with unmodeled dynamic and external disturbance. The master input interface has designed by the impedance properties of the interaction between slave and remote environment. The proposed interface has also relaxed the requirement of the LMI condition and the measurement of the input interaction forces with master and slave manipulator. Evaluation results have presented to demonstrate the effectiveness of the theoretical development for real-time applications.

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