Torque Reflecting Coordination Control for Bilateral Shared Autonomous System Over Open Communication Networks

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***Abstract*—In this paper, torque reflection based coordination control algorithm is designed for network-based bilateral shared autonomous system over open communication networks. The control algorithm for master and slave manipulator is designed by combining delayed position and velocity signal with the delayed reflected torques from the interaction between human and master and between slave and environment. Robust and adaptive control technique is used to deal with uncertainty associated with the gravity, unmodeled dynamic and other external input disturbance. The convergence of the closed loop system is shown by using Lyapunov method. In contrast with existing force reflection based design, the proposed controller can deal with uncertainty associated with the gravity, unmodeled dynamic and external input disturbance. Compared with other methods, the proposed design uses reflected torques from the interaction between master and human and between slave and environment so as to improve the transparency of the bilateral shared autonomous system. Finally, evaluation results are presented to demonstrate the validity of the proposed design for real-time applications.**

I. Introduction

Torque reflection from remote interaction between slave and environment plays significant role to achieve perfect transparency in bilateral shared autonomous system. The transparency guarantees that the local operator can feel the same interaction force as the remote slave feels while interacting with the remote environment [11,18]. The results in this direction can be found in [2, 5, 11, 12, 16, 17, 18, 19, 22, 23, 25]. State reflection based motion synchronization of master and slave manipulator under delay can be found in [1, 3, 4, 7, 8, 9, 13, 14, 15, 20, 21, 24, 28, 29, and many others]. These designs can be used to reproduce the motion of the master manipulator generated by human operators force at the remote slave manipulator. However, to achieve transparent bilateral shared autonomous system, it is also very important to combine force/torque reflection with the state reflection signals. Authors in [2] developed a technique for reducing wave reflection in wave-based shared autonomous system for unknown remote environment under constant time delay. The effect of hard environment interaction force in force reflecting framework has been presented in [5]. In [12], authors developed bilateral shared autonomous system by using force reflection and impedance control. In [16, 17], authors developed projection based force reflecting control algorithms for bilateral shared autonomous systems. Position and force reflection based bilateral shared autonomous system was proposed in [19] by linear network model of a master and slave system. Authors in [22] developed position-force reflection based control scheme in the presence of delay.
Recently, in [23] authors proposed position/position-velocity and torque reflection based control system for bilateral shared autonomous system with delay. The design and stability analysis requires the dynamical model of the master and slave system. State and force reflection based control interface proposed for bilateral shared autonomous system under unsymmetrical delay in [25]. Like the existing force/torque reflection based design, the design does not consider the uncertainty associated with unmodeled dynamic and external disturbance. Model predictive control technique using motion and scaled force signals was also implemented and evaluated for bilateral shared autonomous system in [28].
In this work, we propose state and torque reflection based coordination control interaction strategy for network-based bilateral shared autonomous system under asymmetrical delay and uncertainty. The input interface for the master manipulator is designed by combining delayed position and velocity signals of the slave manipulator with the reflected environment torque applied to the slave manipulator. The slave input interface is developed by comprising delayed position and velocity signals of the master manipulator with the reflected human torques applied to the master manipulator. The local velocity signals are also included to provide additional damping with the input interface of the master and slave manipulator. Robust and adaptive term uses for both master and slave input interface to cope with uncertainty associated with the unmodeled dynamic, external disturbance and gravity. Compared with other torque reflection based interaction interface, the proposed design is robust and can compensate uncertainty associated with master and slave system. Unlike exiting design, the proposed interface reflected torques from the interaction between master and operator and between environment and slave. The convergence analysis for the closed loop system is derived by using Lyapunov method under asymmetrical time varying delay. Evaluation results are presented to illustrate the effectiveness of the proposed method for real-time applications.
The rest of the paper is organized as follows: Section II

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describes the dynamical model and property of the bilateral shared autonomous system. Section II derives coordination control interaction interface algorithm. Convergence analysis is also given in section II. Section III presents experimental results of the proposed method. Finally, section IV concludes the paper.

II. Dynamics, Algorithm Design and Convergence Analysis

Let us first present the dynamical model of the bilateral shared autonomous system. The motion dynamics for n-DOF local master and remote slave manipulator with the human and environment input interaction torques can be derived by the following equation

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

where, $\mathcal{I}_m = (\tau_h + \tau_{dm})$, $\mathcal{I}_s = (\tau_e + \tau_{ds})$, τ_m and τ_s are the control input vectors, $\tau_h = J_m(x_m)^T F_h$ and $\tau_e = J_s(x_s)^T F_e$ are the human and environment torques, F_h and F_e are the applied forces to the master and slave by human and environment, τ_h and τ_e are the interaction torques between master and human and between slave and environment, τ_{dm} and τ_{ds} are the input torques uncertainties associated with unmodeled dynamic and external disturbance, $\ddot{x}_m$, $\dot{x}_m$, 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 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, J_m and J_s are the Jacobian matrices for the master and slave manipulator, m and s represents the master and slave systems, respectively. The interaction torques and torques uncertainty and their first derivatives are assumed to be continuous and bounded. Then, the torque reflecting coordination control for bilateral shared autonomous system can be designed as

$$\begin{aligned} \tau_m &= -k_{dm}\left(\dot{x}_m - \dot{x}_s(t-\mathcal{D}_{ds}(t))\right) + \hat{\theta}_m sgn(\dot{x}_m) \\ &\quad -k_{pm}\left(x_m - x_s(t-\mathcal{D}_{ds}(t))\right) - \xi_{ef}(t-\mathcal{D}_{ds}(t)) \\ &\quad -s_m\dot{x}_m \\ \dot{\hat{\theta}}_m &= -\Gamma_m \dot{x}_m^T sgn(\dot{x}_m) \end{aligned} \quad (2)$$

$$\begin{aligned} \tau_s &= k_{ds}\left(\dot{x}_m(t-\mathcal{D}_{dm}(t)) - \dot{x}_s\right) - k_{ps}x_s + \tilde{\theta}_s sgn(\dot{x}_s) \\ &\quad +k_{ps}x_m(t-\mathcal{D}_{dm}(t)) - \xi_{hf}(t-\mathcal{D}_{dm}(t)) - s_s\dot{x}_s \\ \dot{\hat{\theta}}_s &= -\vartheta_s \dot{x}_s^T sgn(\dot{x}_s) \end{aligned} \quad (3)$$

where $\vartheta_s = \Gamma_s\zeta_s$, $\zeta_s = \frac{k_{pm}}{k_{ps}}$, $\Gamma_s > 0$, $\Gamma_m > 0$, $\xi_{ef}(t-\mathcal{D}_{ds}(t)) = J_s^T k_h F_e(t-\mathcal{D}_{ds}(t))$, $\xi_{hf}(t-\mathcal{D}_{dm}(t)) = J_m^T k_e F_h(t-\mathcal{D}_{dm}(t))$, $s_m > 0$, $s_s > 0$, $k_h > 0$, $k_e > 0$, $k_{pm} > 0$, $k_{dm} > 0$, $k_{ps} > 0$, $k_{ds} > 0$, $\mathcal{D}_{dm}(t)$ and $\mathcal{D}_{ds}(t)$ are the forward and backward asymmetrical data transmission delays. $\hat{\theta}_m$ and $\hat{\theta}_s$ are the estimate of $\|\tau_{dm} - G_m(x_m)\| \le \theta_m$ and $\|\tau_{ds} - G_s(x_s)\| \le \theta_s$ according to property [10] and boundedness property of τ_{dm} and τ_{ds}. Using (1), (2) and (3), we can derive the closed loop system as

$$\begin{aligned} \ddot{x}_m &= M_m^{-1}(x_m)[k_{dm}\dot{x}_s(t-\mathcal{D}_{ds}(t)) - k_{pm}x_m - k_{dm}\dot{x}_m \\ &\quad -C_m(x_m,\dot{x}_m)\dot{x}_m + \tilde{\theta}_m sgn(\dot{x}_m) + \tilde{\tau}_{ef}(t-\mathcal{D}_{ds}(t)) \\ &\quad +k_{pm}x_s(t-\mathcal{D}_{ds}(t)) - s_m\dot{x}_m] \\ \ddot{x}_s &= M_s^{-1}(x_s)[k_{ds}\dot{x}_m(t-\mathcal{D}_{dm}(t)) - C_s(x_s,\dot{x}_s)\dot{x}_s - \\ &\quad k_{ps}x_s + \tilde{\theta}_s sgn(\dot{x}_s) + k_{ps}x_m(t-\mathcal{D}_{dm}(t)) - k_{ds}\dot{x}_s \\ &\quad +\tilde{\tau}_{hf}(t-\mathcal{D}_{dm}(t)) - s_s\dot{x}_s] \end{aligned} \quad (4)$$

with $\tilde{\tau}_{ef}(t-\mathcal{D}_{ds}(t)) = (\tau_h - \xi_{ef}(t-\mathcal{D}_{ds}(t))$ and $\tilde{\tau}_{hf}(t-\mathcal{R}_{dm}(t)) = (\tau_e - \xi_{hf}(t-\mathcal{D}_{dm}(t))$. For convergence analysis, we choose the following Lyapunov function candidate

$$\begin{aligned} &\dot{x}_m^T M_m(x_m)\dot{x}_m + \zeta_s\dot{x}_s^T M_s(x_s)\dot{x}_s + \Gamma_s^{-1}\tilde{\theta}_s^T\tilde{\theta}_s + \mathcal{B}_{Dm} \\ &\int_{(t-\mathcal{D}_{dm}(t))}^{t} \dot{x}_m^T(\eta)\dot{x}_m(\eta)d\eta + \mathcal{G}_{Ds}\int_{(t-\mathcal{D}_{ds}(t))}^{t} \dot{x}_s^T(\eta) \\ &\dot{x}_s(\eta)d\eta + \pi_p\left(x_m - x_s\right)^T\left(x_m - x_s\right) + \Gamma_m^{-1}\tilde{\theta}_m^T\tilde{\theta}_m \\ &+\int_{-\mathcal{A}_{dm}}^{0}\int_{(t+\xi)}^{t} \dot{x}_m^T(\eta)\dot{x}_m(\eta)d\eta d\xi + \int_{-\mathcal{A}_{ds}}^{0}\int_{(t+\xi)}^{t} \dot{x}_s^T(\eta) \\ &\dot{x}_s(\eta)d\eta d\xi \end{aligned} \quad (5)$$

where $\mathcal{B}_{Dm} = \delta_o\left(1 - |\dot{\mathcal{D}}_{dm}(t)|\right)^{-1}$, $\mathcal{G}_{Ds} = k_{dm}\left(1 - |\dot{\mathcal{R}}_{ds}(t)|\right)^{-1}$, $\alpha_o = \zeta_s k_{ds}$, $|\mathcal{D}_{dm}| \le \mathcal{A}_{dm}$, $|\mathcal{D}_{ds}| \le \mathcal{A}_{ds}$, $|\dot{\mathcal{D}}_{dm}(t)| \le \delta_{dm} < 1$ and $|\dot{\mathcal{D}}_{ds}(t)| \le \delta_{ds} < 1$.Then, using Lyapunov argument with Barbalat's Lemma [27], we can state the following Theorem.

Theorem 1: *For the given bounds $\mathcal{A}_{dm}$ and $\mathcal{A}_{ds}$, all the states in the closed loop system (4) are bounded and their bounds can be made closed to zero by increasing the values of the control design parameters $s_m > 0$, $s_s > 0$ $k_{pm} > 0$, $k_{dm} > 0$, $k_{ps} > 0$ and $k_{ds} > 0$.*

III. Evaluation Results

In this section, we evaluate the proposed design on a 2-DOF master and slave bilateral shared autonomous system to illustrate the effectiveness for real-world applications. The motion dynamic of a 2-DOF master and 2-DOF slave manipulator interacting with human and environment can be modeled by the following equation

$$\begin{aligned} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + G_m(x_m) &= \tau_m + \mathcal{I}_m \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{q}_s)\dot{x}_s + G_s(x_s) &= \tau_s + \mathcal{I}_s \end{aligned} \quad (6)$$

where $M_m(x_m) = \begin{bmatrix} m_{11m} & m_{12m} \\ m_{21m} & m_{22m} \end{bmatrix}$, $M_s(x_s) = \begin{bmatrix} m_{11s} & m_{12s} \\ m_{21s} & m_{22s} \end{bmatrix}$, $C_m(x_m,\dot{x}_m) = \begin{bmatrix} C_{11m} & C_{12m} \\ C_{21m} & C_{22m} \end{bmatrix}$, $C_s(x_s,\dot{x}_s) = \begin{bmatrix} C_{11s} & C_{12s} \\ C_{21s} & C_{22s} \end{bmatrix}$, $G_m(x_m) = \begin{bmatrix} G_{m1} \\ G_{m2} \end{bmatrix}$, $G_s(x_s) = \begin{bmatrix} G_{s1} \\ G_{s2} \end{bmatrix}$, $\tau_m = \begin{bmatrix} \tau_{m1} \\ \tau_{m2} \end{bmatrix}$, $\tau_s = \begin{bmatrix} \tau_{s1} \\ \tau_{s2} \end{bmatrix}$,

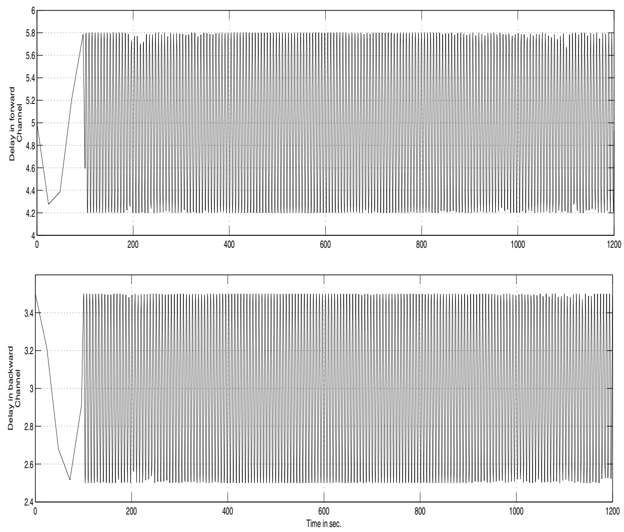

Fig. 1. Data transmission delays in sec..

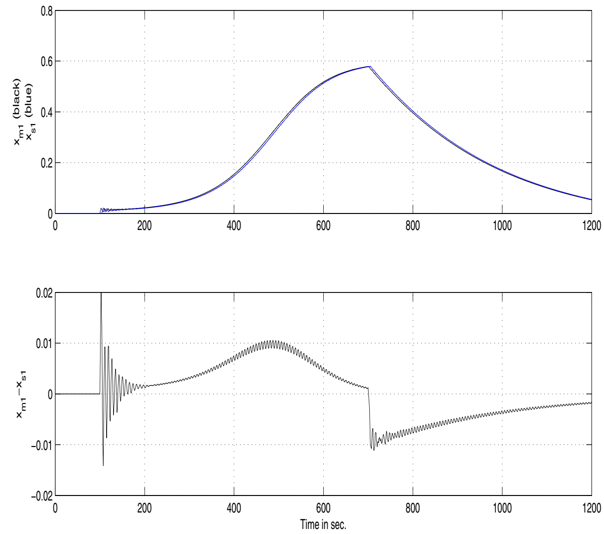

Fig. 3. Time history of the position and tracking error of the master and slave manipulator in joint space in radians.

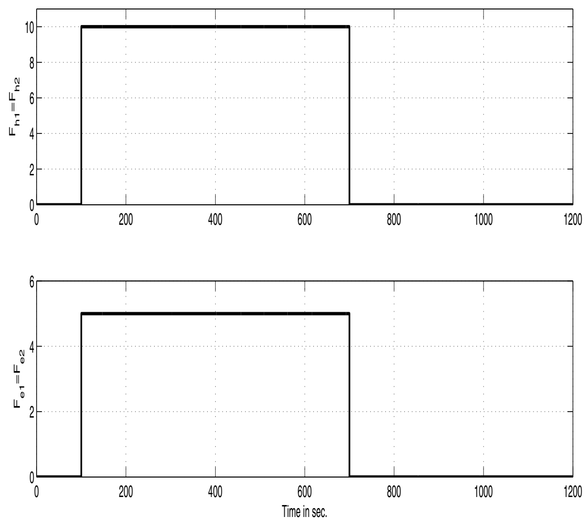

Fig. 2. Applied human $F_{h1} = F_{h2}$ and environment input forces $F_{e1} = F_{e2}$ in Newton with master and slave manipulator.

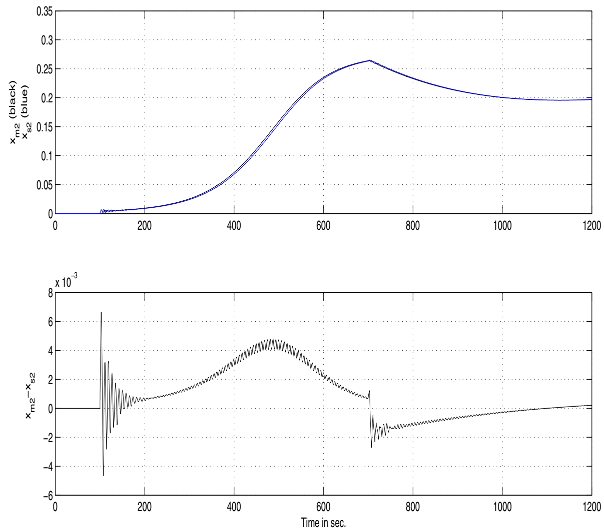

Fig. 4. Position and tracking error profile for the master and slave manipulator in joint space in radians.

$F_h = \begin{bmatrix} F_{h1} \\ F_{h2} \end{bmatrix}$, $F_e = \begin{bmatrix} F_{e1} \\ F_{e2} \end{bmatrix}$, $\tau_{dm} = \begin{bmatrix} \tau_{dm1} \\ \tau_{dm2} \end{bmatrix}$, $\tau_{ds} = \begin{bmatrix} \tau_{ds1} \\ \tau_{ds2} \end{bmatrix}$ 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 mass of the link 1 and link 2 for the master manipulator, m_{1s} and m_{2s} are the mass

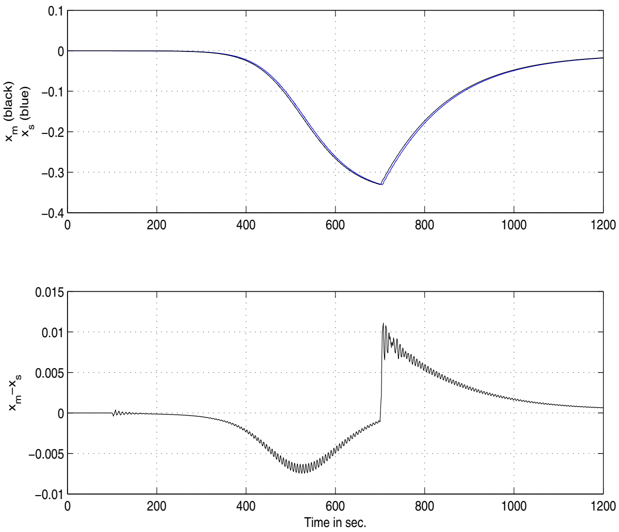

Fig. 5. Position and error trajectory of the master and slave manipulator in Cartesian coordinate space x direction in meter.

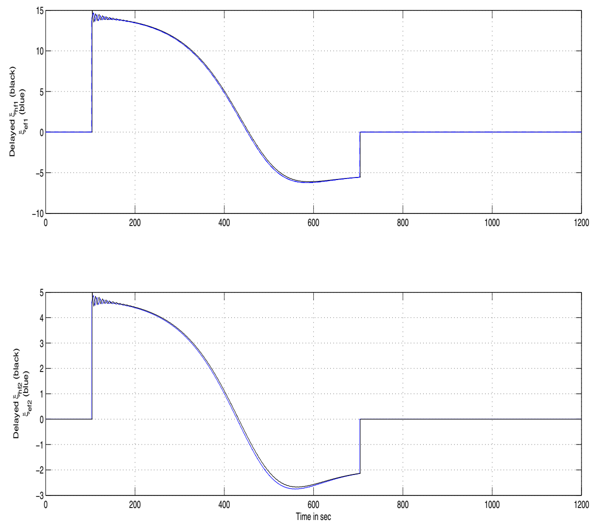

Fig. 7. The delayed reflected input interaction torques profile with master and slave manipulator $\xi_{hf}(t - \mathcal{D}_{dm}(t))$ and $\xi_{ef}(t - \mathcal{D}_{ds}(t))$ in Newton-meter.

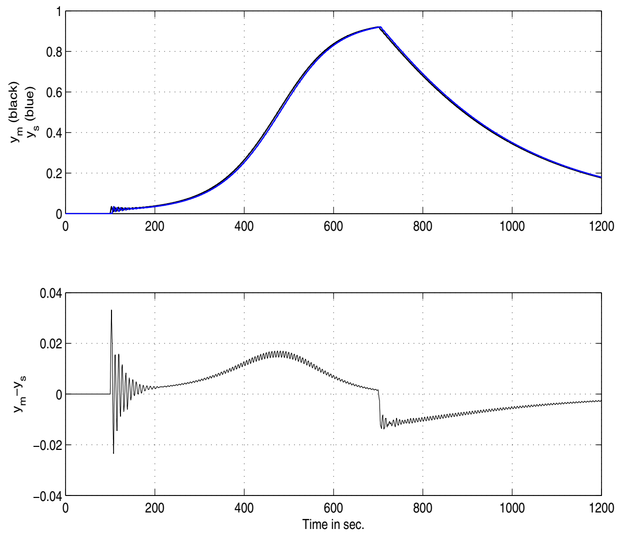

Fig. 6. Position and error trajectory of the master and slave manipulator in Cartesian coordinate space in y direction in meter.

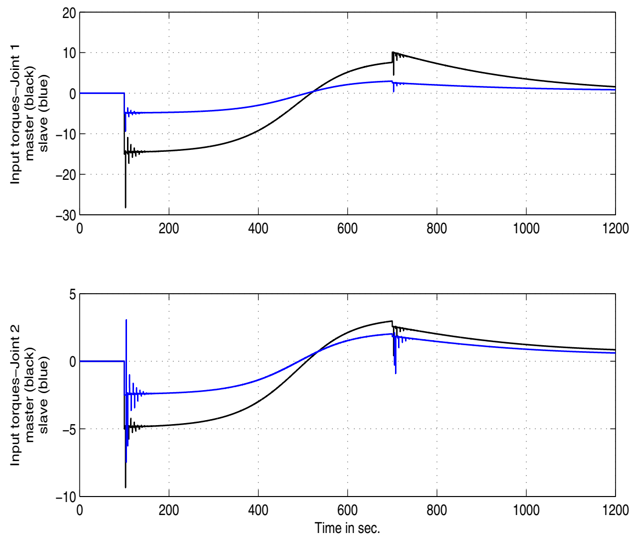

Fig. 8. The input torques for master and slave in Newton-meter.

of the link 1 and link 2 for the slave manipulator. The model parameters for master and slave manipulator are chosen as $m_{1m} = m_{2m} = 0.7kg$, $m_{1s} = m_{2s} = 0.5kg$, $l_{m1} = l_{s1} = 1m$, $l_{m2} = l_{s2} = 0.5m$ and $g = 9.82\frac{m}{s^2}$. The unmodeled dynamic and external input torques disturbance are chosen as $\tau_{dm1} = \tau_{dm2} = 10\sin(t)$ and $\tau_{ds1} = \tau_{ds2} = 10\cos(t)$. The master and slave manipulator is connected by open internet communication channel. The transmission delays over the open communication channel are chosen as shown in Fig. 1. We examine the proposed interaction interface algorithm (2) and (3) for a scenario where the slave manipulator moves in both free space and constraint space. The input interaction forces with master and slave are assumed to be measurable and bounded as depicted in Fig. 2. In our evaluation, we examine the effectiveness of the proposed design by verifying the stability and tracking property of the motion of the master and slave manipulator as well as the forces/torques applied by human and environment to the master and slave manipulator. Specifically, the movement of the slave should follow the movement of the master manipulator. Also, for ensuring the transparent bilateral shared autonomous system, the reflected input interaction torques with master should be equal to the reflected interaction torques with slave manipulator. The design parameters are chosen as $k_{pm} = 400$, $k_{ps} = 500$, $k_{dm} = 600$, $k_{ds} = 800$, $\Gamma_m = 5$, $\Gamma_s = 5\frac{k_{pm}}{k_{ps}}$, $s_m = s_s = 200$. The evaluation results are depicted in Figs. 3 to 8. Figs. 3 to 6 depict the time history of the joint position and error trajectory of the master and slave manipulator. Fig. 7 presents the delayed reflected inputed torques to the master and slave manipulator. The control input torques profile for the master and slave manipulators are shown in Fig. 8. From Figs. 3 to 6, we can see that the slave manipulator can follow the movement of the master manipulator with very small errors in the presence of delay and uncertainty. In view of Fig. 7, we can also notice that the reflected input interaction torques to the master are equal to the reflected input interaction torques to the slave manipulator under asymmetrical delay and bounded uncertainty.

IV. Conclusion

In this paper, we have proposed delay dependent torque reflection based coordination control for bilateral shared autonomous over open communication networks. The master input interface has designed by comprising delayed position and velocity signals with the delayed reflected torques from the interaction between master and operator and interaction between slave and environment. The local position and velocity states have also been used with the input of the master and slave manipulator. We have employed robust adaptive control theory to cope with uncertainty associated with unmodeled dynamic, gravity and other external input disturbance. Lyapunov method used to show the convergence of the states of the closed loop system. The proposed design and analysis does not require LMI condition, exact knowledge of the model dynamics and uncertainties associated with the master and slave system. Evaluation results have presented to demonstrate the theoretical development of the paper.

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