Adaptive Control for Nonlinear Bilateral Teleoperation Manipulators With strong Transparency Performance

Henni Mansour Abdelwaheb and Kacimi Abderrahmane

May 2, 2020

Adaptive Control for Nonlinear Bilateral Teleoperation Manipulators With strong Transparency Performance

1st Henni Mansour Abdelwaheb
Laboratory of Automation and Analysis of the systems
National Polytechnic School of Oran-Maurice Audin-
Oran, Algeria
abdelwahebhenni@gmail.com

2nd Kacimi Abderrahmane
Laboratory of Automation and Analysis of the systems
National Polytechnic School of Oran-Maurice Audin-
Oran, Algeria
kdjoujou@yahoo.fr

***Abstract*—With the advancement of automation and robotics [1]- [4], the bilateral teleoperation system can expand the working capability of human operators in the remote, unstructured and dangerous environments, and has been applied in tremendous areas such as the nuclear detection, medical surgery, subsea exploration and military operation.The main problem in this kind of system is to synchronize the behaviour of the remote and the local robots. In this paper, an adaptive control design is proposed for nonlinear bilateral teleoperation manipulators to cope with the main issues including the communication time delay, various nonlinearities and uncertainties. With the Lyapunov theory, asymptotic stability of the bilateral teleoperation system is suggested to any bounded varying delay with a bounded rate of variation can be guaranteed. Finally, simulation results are presented to demonstrate the validity of our controller.**

***Index Terms*—bilateral teleoperation system, Adaptive control, time varying delay, uncertainties**

I. Introduction

The word teleoperation with the prefix tele meaning at a distance indicates remote operation. Therefore, a tele-operator naturally refers to a master-slave robotic system that permits an operator to interact with a remote environment and finish from a distance manipulation tasks that are inaccessible or hazardous. Such remote systems have applications that include space and undersea exploration [5], robotic surgery [6] and handling of toxic and dangerous materials [7]. A typical teleoperation system is commonly consisting of the operator, the master robot, the communication channel, the slave robot, and the task environment [8]- [9], (Fig. 1).

These teleoperation systems are called bilateral because information flows in two directions between the operator and the remote environment. An essential requirement in bilaterally controlled teleoperation systems is to provide a stable feedback where time-delay in the communication channel between the master and slave systems is the major challenge that threatens system stability. Moreover, external disturbance and uncertainty in the dynamic model parameters are unavoidable issues that should be considered in practical teleoperation systems in order to ensure stable teleoperation system with optimal performance for the designed synchronization controller. In recent past, various control methods for teleoperation systems have been reported in the literature to deal with the problem associated with time delay in the communication channel, e.g. [10]- [16] . Some studies have proposed controllers for ensuring position and force tracking in a nonlinear teleoperation system, but these controllers only work for slowly-varying delays [17]- [18]. Other control methods that guarantee both position and force tracking are either for no-delay or constant-delay nonlinear teleoperation or for linear teleoperation [19]- [20]. Anderson and Spong [21] proposed scattering schemes based on the passivity theory. Passivity based control schemes are inspired from energy interaction between interconnected systems [22].This passivity based approaches can guarantee the passivity of bilateral teleoperation systems just for constant time delay and cannot preserve the passivity for varying time delays [23]. One of the best known methods in the passivity approach are the wave variable approaches, and have been the subject of recent studies concerning teleoperation under varying delays. The wave variable scheme, however only analyzes the passivity of the communication channel in isolation which is overly conservative, and from unwanted wave reflection effects suffers in terms of performance particularly for larger time delays. In this paper, an adaptive synchronization is presented to guarantee asymptotic stability of the bilateral teleoperation system in the presence of larger varying time delays, parametric uncertainties and hard interaction input.This paper is organized as follows.Section 2 preliminaries on modeling of bilateral teleoperators, input interaction torques and actuator saturation are provided.The proposed controller and performance analysis are presented in Section 3.Section 4 presents the simulation and evaluation results and Section 5 concludes the paper.

II. Preliminaries

In this part, some preliminaries on modeling of bilateral teleoperators, input interaction torques and actuator saturation are provided.

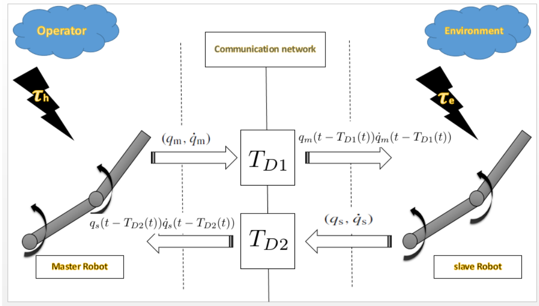

Fig. 1. Bilateral teleoperation system

A. Modeling of bilateral tele-operators

Consider a master-slave bilateral teleoperation system modeled as a pair of n-degree-of-freedom (DOF) serial links with revolute joints, the non-linear dynamics are presented as

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) = \tau_m + \tau_h. \quad (1)$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) = \tau_s + \tau_e \quad (2)$$

where i = m, s stands for the master/slave manipulator, respectively; q_i $\dot{q}_i$ and $\ddot{q}_i$ are the position, velocity, and acceleration of the master and slave dynamic systems respectively;$M_i(q_i)$ is the positive-definite inertia matrix;$C_i(q_i, \dot{q}_i)$: is the matrix of centripetal and Coriolis torque; $G_i(q_i)$: is the gravitational torque; τ_h, τ_e are the human-operator torque and the environment torque, respectively; τ_i is the applied control torque. the following properties of the master and slave manipulators will be used [25]:

1 The inertia matrices $M_m(q_m)$ and $M_s(q_s)$ are a symmetric, bounded and positive definite matrices satisfy the inequalities:
 –
$$0 < \mu_m I \leqslant M_m(q_m) \leqslant \mu_m I$$
 –
$$0 < \mu_s I \leqslant M_s(q_s) \leqslant \mu_s I$$
2 The Coriolis matrix $C(q, \dot{q})$ satisfies:
 –
$$\dot{q}^T[1/2\dot{M}(q, \dot{q}) - C(q, \dot{q})]\dot{q} = 0.$$
 –
$$\dot{M}(q) = C(q, \dot{q}) + C^T(q, \dot{q})$$
 –
$$|C(q, \dot{q})\dot{q}| \leqslant \eta\dot{q}^2$$
 Where η is a positive number.
3 Part of dynamics is linear by the suitable parameters selection of master and slave manipulators, which can be derived as:
 –
$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + G_i(q_i) = Y_i(q_i, \dot{q}_i, \ddot{q}_i)\theta_i$$
 Where Y_i is called the dynamic regressor matrix and θ_i is a vector of the manipulator dynamic parameters.

B. Input Interaction Torques

We model the input interaction forces between the human and the master manipulator ; remote environment and slave manipulator as constant as follows [24]:

$$\tau_h = -N - S_m q_m - D_m \dot{q}_m \quad (3)$$

$$\tau_e = M + S_s q_s + D_s \dot{q}_s \quad (4)$$

$S_m \in R^{n\times n}$ and $D_m \in R^{n\times n}$ denote the diagonal and positive definite matrix of the spring and damping constants of the interaction torque between human and master manipulator, respectively, and $S_s \in R^{n\times n}$ and $D_s \in R^{n\times n}$ denote the diagonal and positive definite matrix of the spring and damping constants of the interaction torque between slave and environment, respectively, N and M are vectors with positive elements.

Note: Human and environment interaction forces play a significant role in achieving desired transparency and stability of the whole closed loop teleoperation systems. These forces are very complex. Many teleoperation systems consider that the input interaction forces are passive, which is very difficult to satisfy in reality, where the slave interacts with uncertain and hard remote environment which opposes the movement of the human operator. Then, the input forces from human and environment to the teleoperators may become non passive.

C. Actuator saturation

In order to save our actuators from the high command signals specially in the transitive regime and hard contact motion which have a direct effect on the transparency and performance of the bilateral system, we use the following actuator saturation:

$$S = \begin{cases} > B & U > B \\ = U & -B \leq U \leq B \\ < -B & U < -B \end{cases}$$

Where M is the saturation bound; U is the value of the command signal; and S is the output of our saturation block.

III. Control Design

In this section, we present our proposed controller to cope with the large varying time delays in bilateral system. We consider also that the dynamics of the system is not exact. Thus, the estimates of the robots dynamics are employed in the controllers τ_m and τ_s above and beyond the various nonlinearities of the model.

A. Adaptive controller design

Let us first define the joint's position error e_p, the joint's velocity errors e_v and the $\varepsilon' s$ error as follows:

$$e_{pm} = q_s(t - T_2(t)) - q_m(t)$$

$$e_{ps} = q_m(t - T_1(t)) - q_s(t)$$

$$e_{vm} = \dot{q}_s(t - T_2(t)) - \dot{q}m(t)$$

$$e_{vs} = \dot{q}_m(t - T_1(t)) - \dot{q}_s(t)$$

$$\varepsilon_i = \dot{q}_i - e_{pi}$$

Where T_1 and T_2 are The forward and backward time delays respectively. Note that the velocity error and the derivative of the position error are not the same because of the variation of time delays. The controllers that will drive the system to the strong transparency and performance are designed as follows:

$$\tau_m = \tau_{m0} - \tau_{m1} \tag{5}$$

$$\tau_s = \tau_{s0} - \tau_{s1} \tag{6}$$

Where

$$\tau_{m0} = -\hat{M}_m(q_m)\dot{e}_{pm} - \hat{C}_m(q_m, \dot{q}_m)e_{pm} - \hat{G}_m(q_m)$$

$$\tau_{s0} = \hat{M}_s(q_s)\dot{e}_{ps} + \hat{C}_s(q_s, \dot{q}_s)e_{ps} + \hat{G}_s(q_s)$$

$$\tau_{m1} = K_m\varepsilon_m - \frac{1}{2}\dot{e}_{pm} - \frac{1}{2}e_{vm} - \frac{e_{vm}^T(e_{pm} + \dot{e}_{pm} - e_{vm})}{2 \parallel \varepsilon_m \parallel_2^2}\varepsilon_m$$

$$\tau_{s1} = K_s\varepsilon_s - \frac{1}{2}\dot{e}_{ps} - \frac{1}{2}e_{vs} - \frac{e_{vs}^T(e_{ps} + \dot{e}_{ps} - e_{vs})}{2 \parallel \varepsilon_s \parallel_2^2}\varepsilon_s$$

Where ˆ represents estimates of the remote and the local manipulators parameters. Using Property 3, τ_{m0} and τ_{s0} can be written as:

$$\tau_{m0} = Y_i(q_i, \dot{q}_i, \ddot{q}_i)\hat{\theta}_i$$

$$\tau_{s0} = -Y_i(q_i, \dot{q}_i, \ddot{q}_i)\hat{\theta}_i$$

Combining equations (3),(4),(1)and(2), the closed-loop system equations are found as:

$$M_m(q_m)\dot{\varepsilon}_m + C_m(q_m, \dot{q}_m)\varepsilon_m = Y_m(q_m, \dot{q}_m, e_m, \dot{e}_m)\hat{\theta}_m$$

$$-\tau_{m1} + \tau_h. \tag{7}$$

$$M_s(q_s)\dot{\varepsilon}_s + C_s(q_s, \dot{q}_s)\varepsilon_s = Y_s(q_s, \dot{q}_s, e_s, \dot{e}_s)\hat{\theta}_s$$

$$-\tau_{s1} - \tau_e. \tag{8}$$

Hence, $\hat{\theta}_i$ is the adaptive update law for manipulators parameter estimation witch is defined as follow:

$$\dot{\hat{\theta}}_i = \Gamma Y_i^T \varepsilon_i.$$

B. Stability and performance analysis

In the following, we analyze the stability of the bilateral system (1) in free motion ($\tau_e = 0$) and under time varying communication delays using the proposed controller (3),(4).i.e. guaranteed that q_i converges to a constant value, and e_{pi} the position error and $e_{vi}$the velocity error converge to zero. Consider a Lyapunov candidate function as

$$V = \frac{1}{2}\int_{t-T_1(t)}^{t} \dot{q}_m^T\dot{q}_m dt + \frac{1}{2}\int_{t-T_2(t)}^{t} \dot{q}_s^T\dot{q}_s dt$$
$$+\frac{1}{2}\sum_{i\in m,s}[\varepsilon_i^T M_i\varepsilon_i + \hat{\theta}_i^T\Gamma^{-1}\hat{\theta}_i + \frac{1}{2}e_{pi}^T e_{pi}] \tag{9}$$

The time derivative of V is

$$\dot{V} = \sum[\frac{1}{2}\varepsilon_i^T\dot{M}_i\varepsilon_i + \varepsilon_i^T M_i\dot{\varepsilon}_i + \hat{\theta}_i^T\Gamma^{-1}\dot{\hat{\theta}}_i + \frac{1}{2}e_{pi}^T\dot{e}_{pi}]$$
$$+\frac{1}{2}\dot{q}_m^T(t)\dot{q}_m(t) - \frac{1}{2}(1 - \dot{T}_1)\dot{q}_m(t - T_1(t))^T\dot{q}_m(t - T_1(t))$$
$$+\frac{1}{2}\dot{q}_s^T(t)\dot{q}_s(t) - \frac{1}{2}(1 - \dot{T}_2)\dot{q}_s(t - T_2(t))^T\dot{q}_s(t - T_2(t)) \tag{10}$$

Using equation (5) and (6) with the skew-symmetry property(property 2), and after some simplifications, we get

$$\frac{1}{2}\varepsilon_i^T\dot{M}_i\varepsilon_i + \varepsilon_i^T\{-C_i\varepsilon_i + Y_i\hat{\theta}_i - \tau_{i1}\} + \hat{\theta}_i^T\Gamma^{-1}\dot{\hat{\theta}}_i$$
$$= \hat{\theta}_i^T\{Y_i^T\varepsilon_i + \Gamma^{-1}\dot{\hat{\theta}}_i\} - \varepsilon_i^T\tau_{i1} \tag{11}$$

We introduce now the adaptive law $\dot{\hat{\theta}}_i = \Gamma Y_i^T\varepsilon_i$ and the definition of τ_{i1} ,$\dot{V}$ can be further simplified as

$$\dot{V} = \sum[-\varepsilon_i^T K_i\varepsilon_i + \frac{1}{2}\varepsilon_i^T\dot{e}_{pi} + \frac{1}{2}\varepsilon_i^T e_{vi}$$
$$+\frac{1}{2}e_{vi}^T(e_{pi} + \dot{e}_{pi} - e_{vi}) + \frac{1}{2}e_{pi}^T\dot{e}_{pi}]$$
$$+\frac{1}{2}\dot{q}_m(t)^T\dot{q}_m(t) - \frac{1}{2}(1 - \dot{T}_1)\dot{q}_m(t - T_1(t))^T\dot{q}_m(t - T_1(t))$$
$$+\frac{1}{2}\dot{q}_s(t)^T\dot{q}_s(t) - \frac{1}{2}(1 - \dot{T}_2)\dot{q}_s(t - T_2(t))^T\dot{q}_s(t - T_2(t)) \tag{12}$$

We have

$$\frac{1}{2}\dot{q}_m(t)^T\dot{q}_m(t) - \frac{1}{2}\dot{q}_s(t - T_2)^T\dot{q}_s(t - T_2(t))$$
$$= -\frac{1}{2}e_{vm}^T e_{vm} - \dot{q}_m(t)^T e_{vm}$$

$$\frac{1}{2}\dot{q}_s(t)^T\dot{q}_s(t) - \frac{1}{2}\dot{q}_m(t - T_1)^T\dot{q}_m(t - T_1(t))$$
$$= -\frac{1}{2}e_{vs}^T e_{vs} - \dot{q}_s(t)^T e_{vs}$$

Then

$$\dot{V} = \sum[-\varepsilon_i^T K_i\varepsilon_i + \frac{1}{2}\varepsilon_i^T\dot{e}_{pi} + \frac{1}{2}\varepsilon_i^T e_{vi}$$
$$+\frac{1}{2}e_{vi}^T(e_{pi} + \dot{e}_{pi} - e_{vi}) + \frac{1}{2}e_{pi}^T\dot{e}_{pi}] - \frac{1}{2}e_{vm}^T e_{vm} - \dot{q}_m(t)^T e_{vm}$$
$$+\frac{1}{2}\dot{T}_1\dot{q}_m(t - T_1(t))^T\dot{q}_m(t - T_1(t)) - \frac{1}{2}e_{vs}^T e_{vs} - \dot{q}_s(t)^T e_{vs}$$

$$+\frac{1}{2}\dot{T}_2\dot{q}_s(t-T_2(t))^T\dot{q}_s(t-T_2(t)) \quad (13)$$

Applying the following relationships

$$\dot{e}_{pm} = e_{vm} - \dot{T}_2\dot{q}_s(t-T_2(t))$$
$$\dot{e}_{ps} = e_{vs} - \dot{T}_1\dot{q}_m(t-T_1(t))$$
$$\dot{q}_m(t-T_1(t)) = e_{vs} + \dot{q}_s$$
$$\dot{q}_s(t-T_2(t)) = e_{vm} + \dot{q}_m$$

$\dot{V}$ is further simplified to

$$\dot{V} = \sum[-\varepsilon_i^T K_i\varepsilon_i + \frac{1}{2}\varepsilon_i^T\dot{e}_{pi} + \frac{1}{2}\varepsilon_i^T e_{vi}$$
$$+\frac{1}{2}e_{vi}^T(e_{pi}+\dot{e}_{pi}-e_{vi}) + \frac{1}{2}e_{pi}^T\dot{e}_{pi} - \frac{1}{2}e_{vi}^T e_{vi} - \dot{q}_i(t)^T e_{vi}$$
$$+\frac{1}{2}(e_{vi}+\dot{q}_i)^T(e_{vi}-\dot{e}_{pi})] \quad (14)$$

More simplification gives

$$\dot{V} = \sum[-\varepsilon_i^T K_i\varepsilon_i - \frac{1}{2}e_{vi}^T e_{vi} + \frac{1}{2}\{\varepsilon_i - \dot{q}_i(t) + e_{pi}\}^T\dot{e}_{pi}$$
$$+\frac{1}{2}\{\varepsilon_i - \dot{q}_i(t) + e_{pi}\}^T e_{vi}] \quad (15)$$

Using the definition of ε_i, it is seen that

$$\dot{V} = -\sum[\varepsilon_i^T K_i\varepsilon_i + \frac{1}{2}e_{vi}^T e_{vi}] < 0; \quad (16)$$

Which shows that V is positive bounded decreasing function and all terms in V are bounded, as a result, the asymptotic stability of our bilateral system under varying time delays is guaranteed.

IV. Simulation results

In this section, simulation results are provided to show the effectiveness of the proposed controller developed in previous sections.In our evaluation, 2-DOF master and slave haptic manipulators are used in local and remote sites connected by telecommunication channel. The master and slave manipulator dynamics have the following inertia, Coriolis/centrifugal, and gravity matrices/vector:

$$M_i(q_i) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, C_i(q_i,\dot{q}_i) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$

and

$$G_i(q_i) = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$

where $M_{11} = m_2l_2^2+(m_1+m_2)l_1^2+2m_2l_1l_2c_2$, $M_{12} = M_{21} = m_2l_2^2 + m_2l_1l_2c_2$, $M_{22} = m_2l_2^2$, $C_{11} = -2m_2l_1l_2s_2\dot{q}_2$, $C_{12} = -m_2l_1l_2s_2\dot{q}_2$, $C_{21} = m_2l_1l_2s_2\dot{q}_1$, $C_{22} = 0$, $G_1 = m_2gl_2c_{12} + g(m_1+m_2)l_1c_1$, $G_2 = m_2gl_2c_{12}$, q_1 and q_2 are the position of the first and the second revolute joints, l_1 and l_2 are the link lengths and m_1 and l_2 are the masses of first and the second links for each robot.And $c_1 = cos(q_1)$,$c_2 = cos(q_2)$,$c_{12} = cos(q_1+q_2)$, $s_1 = sin(q_1)$,$s_2 = sin(q_2)$,$s_{12} = sin(q_1+q_2)$. the physical parameters of the manipulators are set to $m_1 = 3.4Kg$, $m_2 = 0.25Kg$, $l_1 = 1m$, $l_1 = 1m$ and the controller gain K_i is set to 30I.

We consider that $M_m(q_m) = M_s(q_s)$, $C_m(q_m,\dot{q}_m) = C_s(q_s,\dot{q}_s)$, $G_m(q_m) = G_s(q_s)$ and $K_m = K_s = 30$. For both manipulators, we used the same linear parameterization $Y_i(q_i,\dot{q}_i,e_{pi},\dot{e}_{pi})$ as in [26] and we take -70 $\leq U \leq$ 70 for the actuator saturation bounds, where U is the command signal.

To demonstrate the superiority of our controller, we performed three scenarios of teleoperation simulation experiments with the symmetrical time-varying delay $(T_1(t) = T_2(t))$ presented in Fig.2.In the first and the second experiment,free motion and contact motion cases are considered,respectively.In the third experiment,in order to evaluate the robustness and the transparency of the system using the proposed controller,we give master and slave robot a hard interaction input and moving a way the upper bound of time-varying delay T_{upper}=1.6s.

A. Free Motion ($\tau_e = 0$)

In this case, the slave robot does not contact the environment.However, the operator force is described as (3).the parameters for human input force is chosen as: N = 45I , S_m = 30I, D_m = 60I.

From Figs.3-5 ,we can see that position and velocity tracking are achieved. Besides,the position error converge to zero which concluded a nice transparency when using the proposed scheme.

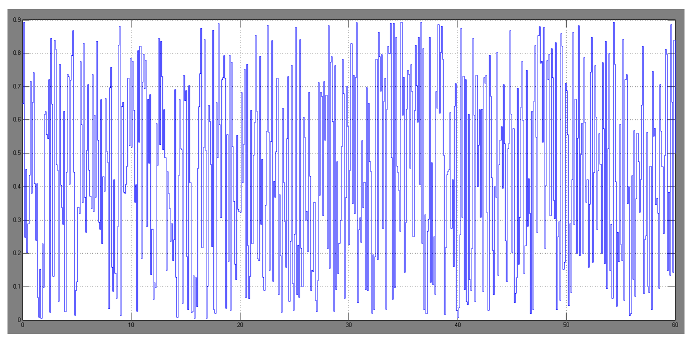

Fig. 2. Variable time delays in the local and remote communication channel

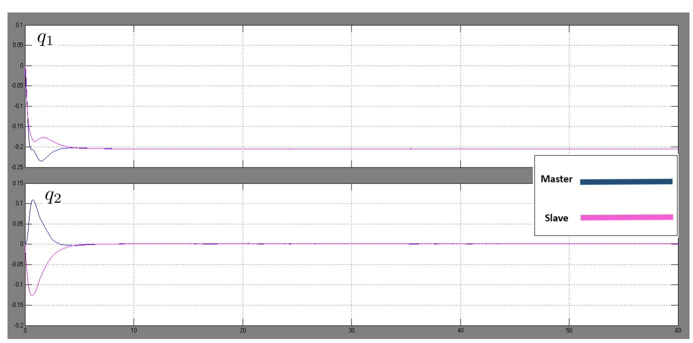

Fig. 3. First and second joint positions of the master and slave robots in free motion

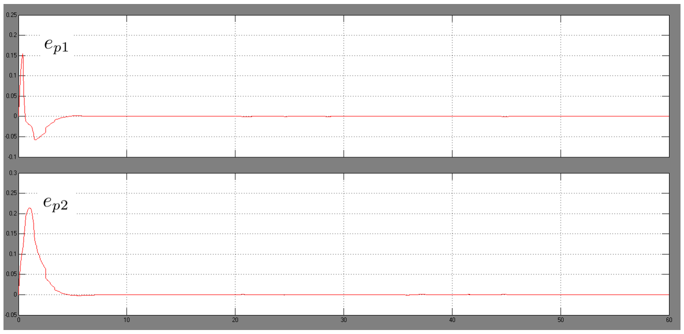

Fig. 4. Position tracking errors in free motion.

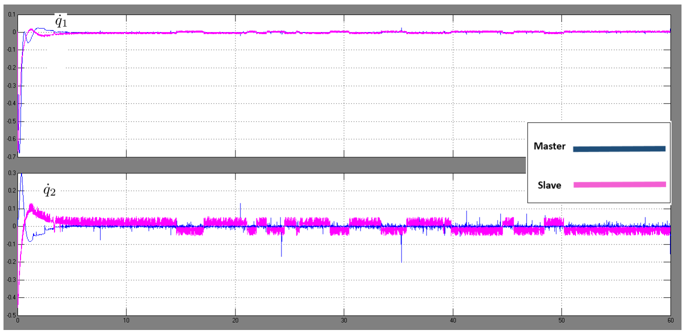

Fig. 5. First and second joint velocities of the master and slave robots in free motion.

B. Cantact Motion ($\tau_e \neq 0$)

In this case,the slave robot contacts the environment which is described as (4). Let's take the parameters for environment input force the same as those for human operator :
M = 45I , S_s = 30I, D_s = 60I.
In Figs. 7 and 9, it can be easily seen that despite variable time delays and the effect of environment force - Fig.6 -, good position and velocity tracking results are also achieved.As can be seen from Fig. 8, using the proposed control scheme, the joint position errors of the master and slave robots converge to zero asymptotically which gives a strong transparency.

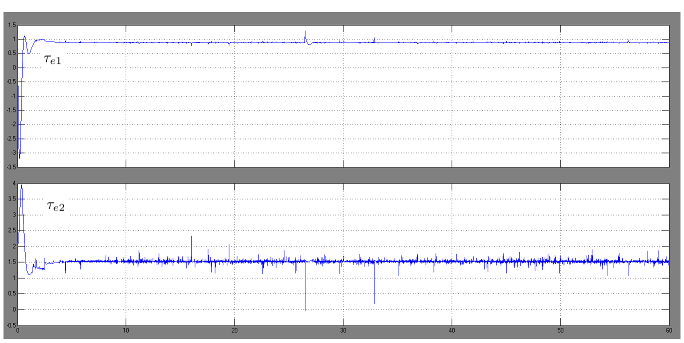

Fig. 6. Environment torque

C. Hard Motion

In this experience, we consider the same interaction input for the human operator and the slave's environment which are

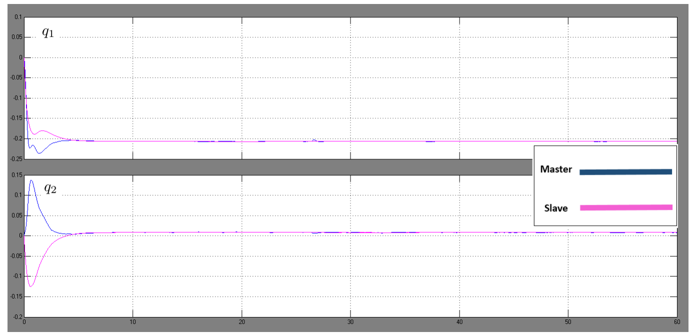

Fig. 7. First and second joint positions of the master and slave robots in contact motion.

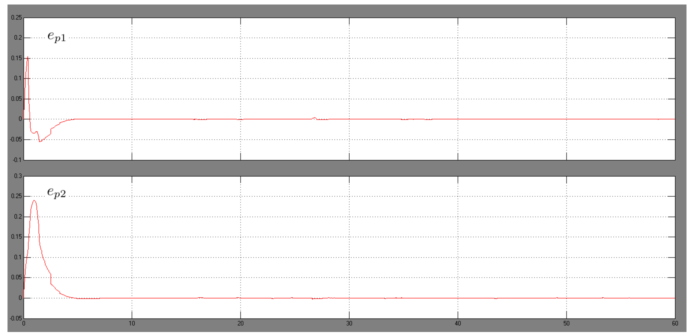

Fig. 8. Position tracking errors in free motion.

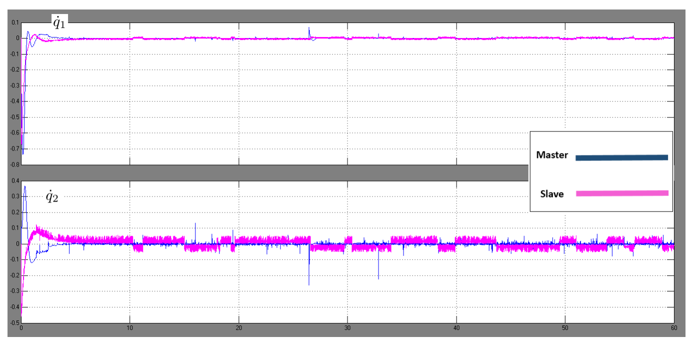

Fig. 9. First and second joint velocities of the master and slave robots in contact motion.

presented in Fig.10. From Figs.11-13, It is remarkable that state synchronization of the bilateral teleoperation system is satisfied in the presence of a large varying communication delays and in a hard interaction input.In Fig.12, tracking errors are asymptotically converging to zero as predicted by the theory.

V. CONCLUSION

In this work,an adaptive synchronization control for bilateral teleoperation systems is presented in the presence of a large varying time delays, parametric uncertainties and hard interaction input. Using $LyapunovKrasovskii$ theory, asymptotic synchronization is proved and finally illustrated by three scenarios of teleoperation simulation experiments.

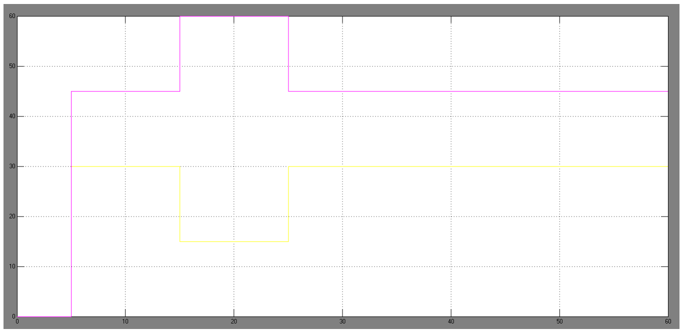

Fig. 10. First and second joint interaction input in hard motion.

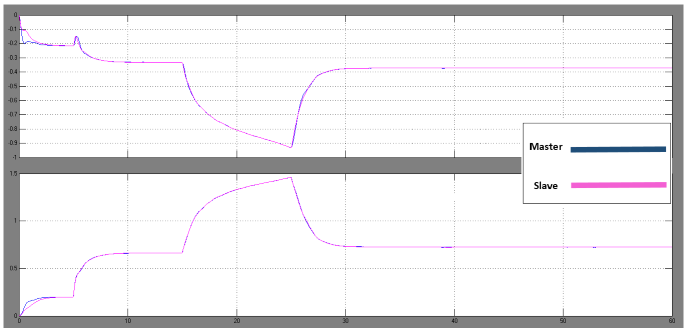

Fig. 11. First and second joint position of the master and slave robots in hard motion.

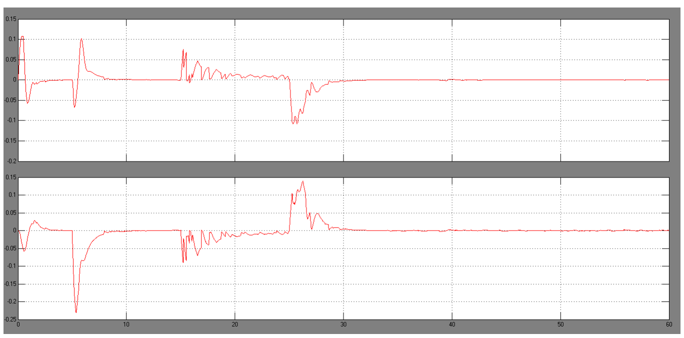

Fig. 12. First and second joint position error of the master and slave robots in hard motion.

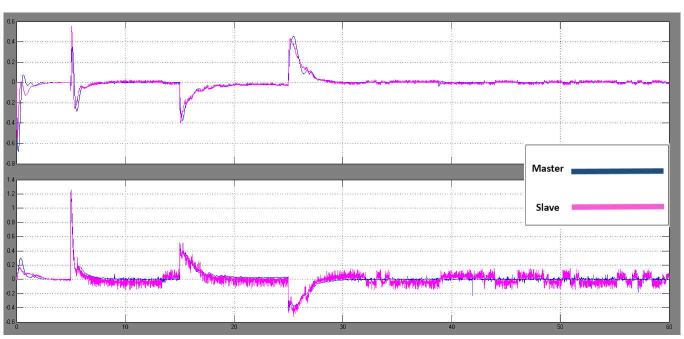

Fig. 13. First and second joint velocities of the master and slave robots in hard motion.

REFERENCES

[1] P.F. Hokayem and M.W. Spong, Bilateral teleoperation: An historical survey, Automatica, vol. 42, no. 12, pp. 20352057, 2006.

[2] Y. Wang, F. Yan, J. Chen, F. Ju, and B. Chen, A New Adaptive Time delay Control Scheme for Cable-driven Manipulators, IEEE Trans. Ind. Inf., vol. 15, no. 6, pp. 34693481, 2019.

[3] J. Yao and W. Deng, Active Disturbance Rejection Adaptive Control of Hydraulic Servo Systems, IEEE Trans. Ind. Electron., vol. 64, no. 10, pp. 8023-8032, 2017.

[4] C. Li, C. Li, Z. Chen and B. Yao, Advanced Synchronization Control of a Dual-linear-motor-driven Gantry With Rotational Dynamics, IEEE Trans. Ind. Electron., vol. 65, no. 9, pp. 7526-7535, 2018.

[5] L. F. Penin, K. Matsumoto, and S. Wakabayashi, Force reflection for time-delayed teleoperation of space robots, in: Proceedings of ICRA'00 IEEE International Conference on Robotics and Automation, 2000, pp. 31203125.

[6] C. Preusche, T. Ortmaier, G. Hirzinger, Teleoperation concepts in minimal invasive surgery, Control Eng. Pract. 10 (2002) 12451250.

[7] K.A. Manocha, N. Pernalete, R.V. Dubey, Variable position mapping based assistance in teleoperation for nuclear cleanup, in: Proceedings of the 2001 ICRA IEEE International Conference on Robotics and Automation, 2001, pp. 374379.

[8] W. H. Zhu and S. E. Salcudean, Stability guaranteed teleoperation: An adaptive motion/force control approach, IEEE Trans on Automatic Control, 2000.

[9] T. B. Sheridan, Human supervisory control of robot systems, Procceeding of the IEEE Conf. of Robotic and Automation, San Francisco, 1986.

[10] Polushin I.: Force reflecting teleoperation over wide-area networks. Ph.D. Thesis, Carleton University (2009)

[11] Alise, M., et al.: On extending the wave variable method to multiple-DOF teleoperation systems. IEEE/ASME Trans. Mechatron. 14, 5563 (2009)

[12] Munir, S., Book, W.: Internet-based teleoperation using wave variables with prediction. IEEE/ASME Trans. Mechatron. 7, 124133 (2002)

[13] Hua, C., Liu, P.: Convergence analysis of teleoperation systems with unsymmetric time-varying delays. IEEE Trans. Circuits Syst. II 56, 240244 (2009)

[14] Forouzantabar, A., Talebi, H.A., Sedigh, A.K.: Adaptive neural network control of bilateral teleoperation with constant time delay. Nonlinear Dyn. 67, 11231134 (2012)

[15] Polushin, I., Liu, P., Lung, C.-H.: On the model-based approach to nonlinear networked control systems. Automatica 44, 24092414 (2008)

[16] Oboe, R.: Web-interfaced, force-reflecting teleoperation systems. IEEE Trans. Ind. Electron. 48, 12571265 (2001)

[17] I.G. Polushin, P.X. Liu, C.-H. Lung, G.D. On, Position-error based schemes for bilateral teleoperation with time delay: theory and experiments, J. Dyn. Syst., Meas., Control 132 (2010) 031008.

[18] I.G. Polushin, P.X. Liu, C.-H. Lung, A force-reflection algorithm for improved transparency in bilateral teleoperation with communication delay, IEEE/ASME Trans. Mechatron. 12 (2007) 361374.

[19] X. Liu, M. Tavakoli, Adaptive inverse dynamics four-channel control of uncertain nonlinear teleoperation systems, Adv. Robot. 25 (2011) 17291750.

[20] H. Amini, S. Rezaei, M. Zareinejad, H. Ghafarirad, Enhanced time delayed linear bilateral teleoperation system by external force estimation, Trans. Inst. Meas. Control 35 (2013) 637647.

[21] R.J. Anderson and M.W. Spong, Asymptotic stability for force reflecting teleoperations with time delay, IEEE International Conference on Robotics and Automation, pp. 1618-1625, 1989.

[22] C.A. Desoer and M. Vidyasagar, Feedback systems: Inputoutput properties, New York: Academic Press, 1975.

[23]] P.F. Hokayem and M.W. Spong, Bilateral teleoperation: An historical survey, Automatica, vol. 42 (12), pp. 2035-2057, 2006.

[24] C.-C. Hua, X.P. Liu, Delay-dependent stability criteria of teleoperation systems with asymmetric time-varying delays, IEEE Trans. Robot. 26 (2010) 925932.

[25] Kelly,R., Santibanez,V., Loria,A.: Control of Robot Manipulators in Joint Space (Advanced Textbooks in Control and Signal Processing). Springer-Verlag, New York (2005)

[26] E. Nuo, R. Ortega, and L. Basaez, An adaptive controller for nonlinear teleoperators, Automatica, vol. 46 (1), pp. 155-159, 2010.