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An Adaptive Observer-Based Controller Design for Time-Delay Teleoperation with Uncertainty in Environment and Parameters

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Abstract—- **In this paper, the control of time-delay bilateral teleoperation systems is considered. Control complexity of such systems arises due to the nonlinear and uncertain dynamics of the system as well as the latency in data communication between the master and slave sides. Hence, a novel control scheme is proposed in this paper which improves both stability and transparency of the system despite the above mentioned limitations. The proposed controller is composed of two control loops. First, a local Lyapunov-based adaptive controller is applied (in both master and slave sides) to cancel system nonlinearities. Subsequently, a new observer-based controller scheme is proposed to achieve the stability and performance (transparency) objectives. Using the Lyapunov techniques, stability and performance objectives are cast as some Linear Matrix Inequality (LMI) feasibility conditions. Experimental results are presented to illustrate the enhanced performance of the proposed controller methodology.**

I. Introduction

BILATERAL master-slave teleoperation systems provide remote object manipulation for human operators with similar conditions as those of the remote location. Application of such systems is where direct contact with the environment is hazardous or too difficult. Some examples are space explorations, nuclear operations, robotic surgery, etc. The reader is referred to [1] for a historical overview.

It can be verified that control of teleoperation systems is complicated due to a lot of challenges. The dynamics of master and slave robots are often nonlinear and subjected to uncertainty. Another cause of difficulty is the uncertainty presents in the interaction of these robots with unknown and widely varying operator and environment dynamics. Finally, the communication time delay in telerobotic applications is the main obstacle to maintaining both transparency and stability of the system. Communication time delay causes a trade-off between stability and transparency.

Several control schemes have been proposed for teleoperation systems. Some of them are compared in [2] from stability and performance points of view. In several papers Robust H∞-based controller and µ-synthesis have been used for teleoperation system ([3]-[9]). In [3] and [4] the time delay was not considered but the most important problem occurring in teleoperation systems is unknown time delay especially when the communication channel is World Wide Web. In [5], time delay was approximated using a Pad´e approximation but it is clear that the frequency response of low order Pad´e approximation does not mimic the original frequency response especially at high frequencies. A simple and common method is treating time delay as a perturbation to the system as done in [6]-[9]. However such treatment of the delay is unrealistic and because of special frequency response of delay can yield conservative control designs. In [10], a method was introduced based on a continuous-time delay reduction technique and the LQG. However, such model-based LQG controller does not possess enough robustness against uncertainty and good performance in the presence of time delay.

In [11] and [12] an adaptive controller was introduced to eliminate system nonlinearities. Then, a controller is designed to deal with time delay based on recursive adobe problem that was already introduced in [13]. However, the iterative synthesis and implementation of their presented controller is extremely complex.

Linear Matrix Inequality (LMI) is a powerful and easy to implement method to deal with stability and stabilization problems. Based on this approach several controllers were designed for uncertain time delayed systems ([14]-[17]). In [14], a stabilizing controller was designed for a general time delay system. However, no performance measure was guaranteed as a result of applying this controller. In [15],an LMI-based controller was applied to a teleoperation system and achieved good stability in the presence of time delay and uncertainty. However the method was developed for linear model of the system and also no experiment was conducted to support the simulation results.

In this paper, a new method is proposed to deal with time-delay, uncertainties and nonlinearities of the teleoperation system. First, local adaptive controllers are designed on both master and slave sides to eliminate nonlinearities of the system. Then a new observer-based controller based on LMI is designed to deal with time-delay and uncertainties of the system. The main novelty of this paper is introducing a new observer based controller which possesses the optimum performance measure between all stabilizing controllers. Combining adaptive control and the proposed observer-based control is another novelty of this paper.

The rest of the paper is organized as follows. Section II presents designing of local adaptive controllers for master and slave. In Section III the dynamics of the system is given. The robust controller design is introduced in Section IV. Sections V and VI depict simulation and experimental

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results obtained by employing the proposed method. Finally, conclusions are stated in Section VII.

II. LOCAL ADAPTIVE CONTROLLER DESIGN

The dynamics of the master robot incorporating the human operator and the slave robot incorporating the environment can be stated as follows ([11] and [18])

$$\begin{aligned} &\mathcal{M}_m \ddot{X}_m + \mathcal{C}_m \dot{X}_m + \mathcal{G}_m = F_{cm} + F_h^* \\ &\mathcal{M}_m = D_m(X_m) + M_h, \quad \mathcal{C}_m = C_m(\dot{X}_m, X_m) + B_h \\ &\mathcal{G}_m = G_m(X_m) + K(X_m - X_{m0}) \end{aligned} \tag{1}$$

$$\begin{aligned} &\mathcal{M}_s \ddot{X}_s + \mathcal{C}_s \dot{X}_s + \mathcal{G}_s = F_{cs} \\ &\mathcal{M}_s = D_s(X_s) + M_e, \quad \mathcal{C}_s = C_s(\dot{X}_s, X_s) + B_e \\ &\mathcal{G}_s = G_s(X_s) + K_e(X_s - X_{s0}) \end{aligned} \tag{2}$$

where indices *m, s, h, e* indicate master, slave, human operator and environment, respectively. Local adaptive nonlinear controllers used here are similar to those proposed in [19] and also used in [11] for teleoperation system. The local control laws for the master and slave robots are given by

$$F_{cm} = Y_m \hat{\Theta}_m + \mathcal{K}_m (V_{md} - V_m + \tilde{F}_h - \lambda_m X_m) \tag{3}$$

$$F_{cs} = Y_s \hat{\Theta}_s + \mathcal{K}_s (V_{sd} - V_s - \tilde{F}_e - \lambda_s X_s) \tag{4}$$

where V_{md} and V_{sd} are two command vectors to be introduced later, V_m and V_s are velocity vectors, $\mathcal{K}_m$, $\mathcal{K}_s$, A are positive definite diagonal matrices, and $\tilde{F}$ is a filtered force (see Fig.1) $\hat{\Theta}_\gamma$denotes the estimate of Θ_γ that contains all unknown parameters of the master ($\gamma = m$) or slave ($\gamma = s$). Y_m and Y_s are regressor matrices which are defined in [11].

$$\begin{aligned} Y_s \Theta_s &= \mathcal{M}_s \frac{d}{dt}[V_{sd} - \tilde{F}_e - \lambda_s X_s] \\ &\quad + \mathcal{C}_s [V_{sd} - \tilde{F}_e - \lambda_s X_s] + \mathcal{G}_s \end{aligned} \tag{5}$$

$$\begin{aligned} Y_m \Theta_m &= \mathcal{M}_m \frac{d}{dt}[V_{md} - \tilde{F}_h - \lambda_m X_m] \\ &\quad + \mathcal{C}_m [V_{md} - \tilde{F}_h - \lambda_m X_h] + \mathcal{G}_h \end{aligned} \tag{6}$$

The parameter estimate $\hat{\theta}_\gamma$ may be computed using standard methods of adaptive control. For example using the gradient update law

$$\dot{\hat{\Theta}}_{\gamma i} = \rho_{\gamma i} Y_{\gamma i}^T r_\gamma \tag{7}$$

$$r_\gamma = V_{\gamma d} - V_\gamma + \tilde{F}_{h,e} - \beta X_\gamma \tag{8}$$

where the subscript γ_i is assigned to the i^{th} parameter of either master ($\gamma = m$) or slave ($\gamma = s$), $\rho_{\gamma i} > 0$ is a parameter update gain. To avoid getting unallowable values $\hat{\theta}_{\gamma i}$ should be saturated.

By using the Lyapunov theory, it can be concluded that [19]

$$r_\gamma \in \ell_2 \cap \ell_\infty \quad \gamma = m,s \tag{9}$$

LTI models of hand and environment can be stated as

$$f_e = f_e^* + Z_e x_s, \quad f_h = f_h^* + Z_h x_m \tag{10}$$

By using (8), (9), (10) the close loop local dynamics become linear and perturbed by bounded disturbances. Therefore all linear controllers can be implemented on it. A block diagram of the resulting system is shown in Fig. 1. The uncertainty of the hand and environment is introduced as a perturbation to their impedances.

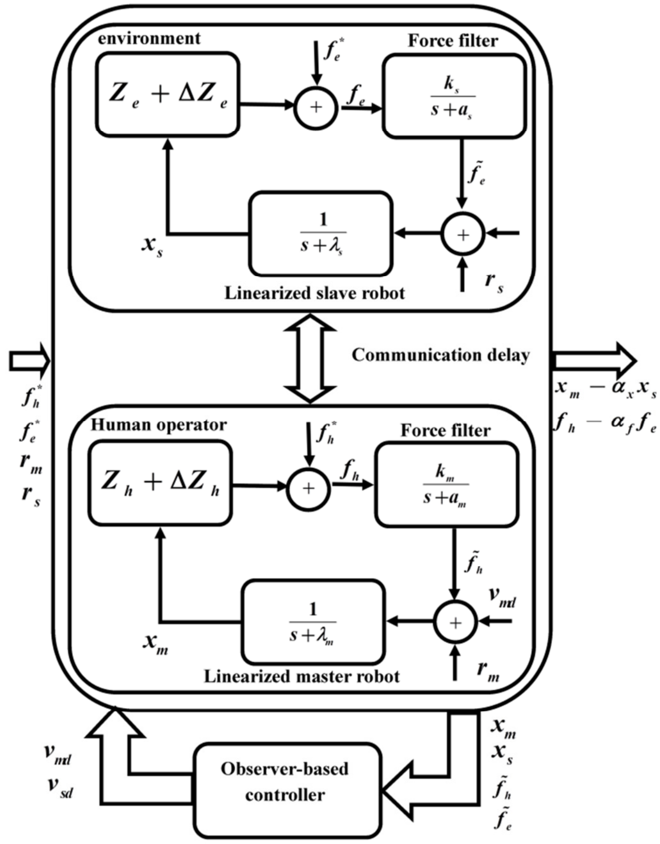

Fig 1. The block diagram of the teleoperation system

III. PROBLEM FORMULATION

As mentioned in the previous section, after using adaptive controller, the dynamics of the system become linear and are subjected to bounded disturbances. Another controller is needed to reject the disturbances and achieve a high level of performance in presence of time delay and uncertainties. In this section the linear dynamics of the system and the general form of an observer-based controller is stated.

The state-space form of the system can be written as:

$$\begin{aligned} \dot{x}(t) &= (A + \Delta A)x(t) + (A_1 + \Delta A_1)x(t-h) \\ &\quad + (B_1 + \Delta B_1)u(t) + B_2 w(t) \end{aligned} \tag{11}$$

$$y(t) = (C_1 + \Delta C_1)x(t) \tag{12}$$

$$z(t) = C_2 x(t) \tag{13}$$

where $x=[x_m, f_m, \tilde{f}_h, x_s, f_s, \tilde{f}_e]$ are system state variables, $u=[v_{md}, v_{sd}]$ are control inputs, w is exogenous inputs $w=[r_m, f_h^*, r_s, f_e^*]$, y is the measurement signals $y=[x_m, f_m, \tilde{f}_h, x_s, f_s, \tilde{f}_e]$ and z is regulated output $z=[x_m-\alpha_x x_s, f_h-\alpha_f f_e]$. It's easy to find A, A_1, B_1, B_2, C_1, C_2 from Fig. 1. Moreover ΔA, ΔA_0, ΔB_1, ΔC_1 represent the uncertainty of the environment and the parameters and are subjected to [14]

$$\Delta A = D_1 F_1(t) E_1, \qquad \Delta A_1 = D_2 F_2(t) E_2, \tag{14}$$

$$\Delta B_1 = D_3 F_3(t) E_3, \qquad \Delta C_1 = D_4 F_4(t) E_4, \tag{15}$$

$$F_i^T(t) F_i(t) \le I \quad i = 1,\ldots,4 \tag{16}$$

The dynamics of observer-based controller has the following form

$$\begin{aligned}\dot{\hat{x}}(t) &= (A + B_1 K - L C_1)\hat{x}(t) + A_1 \hat{x}(t-h) \\ &\quad + B_1 K A_1 \int_{t-h}^{t} \hat{x}(\tau) d\tau + L y(t)\end{aligned} \tag{17}$$

$$u(t) = K(\hat{x}(t) + A_1 \int_{t-h}^{t} \hat{x}(\tau) d\tau) \tag{18}$$

Now the problem is finding gains K and L such that the system stability is guaranteed and the regulated output that indicates transparency of the system is bounded.

IV. The Proposed Robust Outer-Loop Controller

In this section a method for observer-based controller design based on linear matrix inequality is proposed to deal with communication time delay and uncertainty in the environment and parameters. Such work was currently studied as a theorem in [14] but only a stabilizing controller for a general time delay system is proposed. However it's obvious that in teleoperation system in addition to stability, the transparency is of high importance. To achieve such goal, a new theorem is presented that can find the optimum controller with the transparency criterion in all stabilizing controllers. The following theorem presents the main contribution of the paper:

Theorem: Consider the system of the form (11),(12),(13) with constant time delay h. If there exist positive definite matrices X, P, W, V and R , matrices G and H, positive scalar values γ and ε_i $(i=1,\ldots,5)$ that satisfy (19),(20),(21)

$$\begin{bmatrix} F_{x11} & F_{x12} & 0 & hX & X & F_{x16} & F_{x17} \\ * & -Y & F_{x23} & F_{x24} & -YA_1^T & F_{x26} & 0 \\ * & * & -\varepsilon_4 I & 0 & 0 & 0 & 0 \\ * & * & * & -Y & 0 & 0 & 0 \\ * & * & * & * & -W & 0 & 0 \\ * & * & * & * & * & -F_{x66} & 0 \\ * & * & * & * & * & * & -F_{x77} \end{bmatrix} < 0 \tag{19}$$

$$\begin{bmatrix} F_{e11} & F_{e12} & hR & F_{e14} \\ * & -R & F_{e23} & 0 \\ * & * & -R & 0 \\ * & * & * & F_{e44} \end{bmatrix} < 0 \tag{20}$$

$$\begin{bmatrix} -W & WE_2^T & WE_2^T \\ * & -\varepsilon_3 I & 0 \\ * & * & -I \end{bmatrix} < 0 \tag{21}$$

where

$$\begin{aligned}F_{x11} &= A_0 X + X A_0^T + B_1 B_1^T + B_1 G + G^T B^T \\ &\quad + (\varepsilon_1 + \varepsilon_4) D_1 D_1^T + \varepsilon_3 D_2 D_2^T + (1+\varepsilon_2) D_3 D_3^T\end{aligned} \tag{22}$$

$$F_{x12} = -A_0 A_1 Y \tag{23}$$

$$F_{x16} = [XE_1^T, XE_4^T, C_2^T, \sqrt{2}\gamma^{-1} B_2] \tag{24}$$

$$F_{x17} = [XE_1^T, GE_3^T, C_2^T, GE_3^T, C_2^T] \tag{25}$$

$$F_{x23} = YA_1^T E_1^T \tag{26}$$

$$F_{x24} = -hYA_1^T \tag{27}$$

$$F_{x26} = [-YA_1^T E_1^T, -YA_1^T E_4^T, -YA_1 C_2^T, -YA_1 B_2^T] \tag{28}$$

$$F_{x66} = diag\{I, I, I, I\} \tag{29}$$

$$F_{x77} = diag\{\varepsilon_1 I, \varepsilon_2 I, I\} \tag{30}$$

$$\begin{aligned}F_{e11} &= PA_0 + A_0^T P - HC_1 - C_1^T H^T \\ &\quad + X^{-1} G^T G X^{-1} + (1+\varepsilon_5) X^{-1} G^T E_3^T E_3 G X^{-1}\end{aligned} \tag{31}$$

$$F_{e12} = -PA_0 + GC_1 A_1 \tag{32}$$

$$F_{e14} = [PD_1, PD_2, PD_3, PD_3, HD_4, \gamma^{-1} B_2] \tag{33}$$

$$F_{e23} = -hA_1^T R \tag{34}$$

$$F_{e44} = diag\{-I, -I, -I, -\varepsilon_5 I, -I, -I\} \tag{35}$$

$$A_0 = A + A_1 \tag{36}$$

The system with observer-based controller of the form (17), (18) with $K=GX^{-1}$ and $L=P^{-1}H$ is asymptotically stable and the corresponding H_∞ performance is γ ($\|T_{zw}\|_\infty \le \gamma$). To achieve the optimum controller with performance criterion, γ should be minimized.

Proof: Consider the following functional

$$J_1 = V(x,e) + \int_{t=0}^{\infty} (z^T z - \gamma^2 w^T w) dt \tag{37}$$

$V(x,e)$ is Lyapunov function candidate introduced in [14]:

$$V(x,e) = V_1(x) + V_2(e) \tag{38}$$

$$\begin{aligned}V_1(x) &= \mathcal{D}_x^T(x) S \mathcal{D}_x(x) + \int_{t-h}^{t} \int_s^t x^T(u) T x(u) du ds \\ &\quad + \int_{t-h}^{t} x^T(s) U x(s) ds\end{aligned} \tag{39}$$

$$V_2(e) = \mathcal{D}_e^T(e) P \mathcal{D}_e(e) + \int_{t-h}^{t} \int_s^t e^T(u) Q e(u) du ds \tag{40}$$

where operator $\mathcal{D}$ is neutral transformation defined as ([20])

$$\mathcal{D}(x) = x(t) + A_1 \int_{t-h}^{t} x(s) ds \tag{41}$$

Similar to the proof of BRL in [21] the H∞ performance is achieved if

$$\dot{J}_1 = \dot{V}(x,e) + z^T z - \gamma^2 w^T w < 0 \tag{42}$$

Now, if the following inequality holds ([14]),

$$-U + \varepsilon_3^{-1} E_1^T E_1 + E_2^T E_2 < 0 \tag{43}$$

Then

$$\dot{V}_1 \le \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s) ds \end{bmatrix}^T M_x \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s) ds \end{bmatrix} \tag{44}$$

$$\dot{V}_2 \le \begin{bmatrix} \mathcal{D}_e(x) \\ \int_{t-h}^{t} e(s)ds \end{bmatrix}^T M_e \begin{bmatrix} \mathcal{D}_e(x) \\ \int_{t-h}^{t} e(s)ds \end{bmatrix} \tag{45}$$

where

$$M_x = \begin{bmatrix} \Sigma_{x1} + \Pi & -SA_0A_1 - \Pi A_1 \\ * & -h^{-1}T + A_1^T \Pi A_1 + \varepsilon_4^{-1} A_1^T E_1^T E_1 A \end{bmatrix} \tag{46}$$

$$M_e = \begin{bmatrix} \Sigma_{e1} + \Pi & -P(A_0 - LC)A_1 - hQA_1 \\ * & -h^{-1}Q + hA_1^T QA_1 \end{bmatrix} \tag{47}$$

$$\begin{aligned} \Sigma_{x1} = {} & S(A_0 + B_1K) + (A_0^T + K^T B_1^T)S \\ & + (\varepsilon_1 + \varepsilon_4)SD_1D_1^T S + (1+\varepsilon_2)SD_3D_3^T S \\ & + \varepsilon_3 SD_2D_2^T S + SB_1B_1^T S + \varepsilon_1^{-1} E_1^T E_1 \\ & + (1+\varepsilon_2^{-1})K^T E_3^T E_3 K \end{aligned} \tag{48}$$

$$\begin{aligned} \Sigma_{e1} = {} & P(A_0 - LC_1) + (A_0 - LC_1)^T P + K^T K \\ & + PLD_4D_4^T L^T P + (1+\varepsilon_5)K^T E_3^T E_3 K \\ & + PD_1D_1^T P + PD_2D_2^T P \\ & + (1+\varepsilon_5^{-1})PD_3D_3^T P \end{aligned} \tag{49}$$

$$\Pi = hT + U + E_1^T E_1 + E_4^T E_4 \tag{50}$$

On the other hand

$$z^T z = x^T C_2^T C_2 x \tag{51}$$

Substituting *x* from (41) yields

$$z^T z = \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s)ds \end{bmatrix}^T \begin{bmatrix} C_2^T C_2 & -C_2^T C_2 A_1 \\ * & A_1^T C_2^T C_2 A_1 \end{bmatrix} \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s)ds \end{bmatrix} \tag{52}$$

By using (42), (44), (45) and (52) the following inequality yields

$$\begin{aligned} \dot{J}_1 \le {} & \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s)ds \\ w \end{bmatrix} \tilde{M}_x \begin{bmatrix} \mathcal{D}_x(x) \\ \int_{t-h}^{t} x(s)ds \\ w \end{bmatrix} \\ & + \begin{bmatrix} \mathcal{D}_e(e) \\ \int_{t-h}^{t} e(s)ds \\ w \end{bmatrix}^T \tilde{M}_e \begin{bmatrix} \mathcal{D}_e(e) \\ \int_{t-h}^{t} e(s)ds \\ w \end{bmatrix} \end{aligned} \tag{53}$$

where

$$\tilde{M}_x = \begin{bmatrix} \Sigma_{x1} + \Pi & -SA_0A_1 - \Pi A_1 - C_2^T C_2 A_1 & SB_2 \\ * & \tilde{M}_{x22} & 0 \\ * & * & -\frac{1}{2}\gamma^2 I \end{bmatrix} \tag{54}$$

$$\tilde{M}_e = \begin{bmatrix} \Sigma_{e1} + hQ & \tilde{M}_{e12} & SB_2 \\ * & -h^{-1}Q + hA_1^T QA_1 & 0 \\ * & * & -\frac{1}{2}\gamma^2 I \end{bmatrix} \tag{55}$$

$$\begin{aligned} \tilde{M}_{x22} = {} & -h^{-1}T + A_1^T \Pi A_1 + \varepsilon_4^{-1} A_1^T E_1^T E_1 A_1 \\ & + A_1^T C_2^T C_2 A_1 \end{aligned} \tag{56}$$

$$\tilde{M}_{e12} = -P(A_0 - LC)A_1 - hQA_1 \tag{57}$$

From [14] $\tilde{M}_x$ and $\tilde{M}_e$ should be negative definite. By using the schur complement those inequalities are equivalent to

$$\begin{bmatrix} \Sigma_{x1} + \Pi_{new} & -SA_0A_1 - \Pi A_1 - C_2^T C_2 A_1 \\ * & \tilde{M}_{x22} \end{bmatrix} < 0 \tag{58}$$

$$\begin{bmatrix} \Sigma_{e1} + hQ + 2\gamma^{-2} B_2 B_2^T & \tilde{M}_{e12} \\ * & -h^{-1}Q + hA_1^T QA_1 \end{bmatrix} < 0 \tag{59}$$

where

$$\begin{aligned} \Pi_{new} = {} & hT + U + E_1^T E_1 + E_4^T E_4 \\ & + C_2^T C_2 + 2\gamma^{-2} B_2 B_2^T \end{aligned} \tag{60}$$

Once again utilizing schur complement yields in

$$\begin{bmatrix} \Sigma_{x1} & N_{x12} & hI & I & E_1^T & E_4^T & C_2^T & N_{x18} \\ * & N_{x22} & -hA_1^T & -A_1^T & -A_1^T E_1^T & -A_1^T E_4^T & -A_1 C_2^T & 0 \\ * & * & -hT^{-1} & 0 & 0 & 0 & 0 & 0 \\ * & * & * & -U^{-1} & 0 & 0 & 0 & 0 \\ * & * & * & * & -I & 0 & 0 & 0 \\ * & * & * & * & * & -I & 0 & 0 \\ * & * & * & * & * & * & -I & 0 \\ * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \tag{61}$$

$$\begin{bmatrix} \Sigma_{e1} + 2\gamma^{-1} B_2 B_2^T & N_{e12} & hI \\ * & -h^{-1}Q & -hA_1^T \\ * & * & -h^{-1}Q \end{bmatrix} < 0 \tag{62}$$

where

$$N_{x12} = -SA_0A_1 \tag{63}$$

$$N_{x18} = \sqrt{2}\gamma^{-1} B_2 \tag{64}$$

$$N_{x22} = -h^{-1}T + \varepsilon_4^{-1} A_1^T E_1^T E_1 A_1 \tag{65}$$

$$N_{e12} = -PA_0A_1 + PLC_1A_1 \tag{66}$$

Let

$$X = S^{-1}, \quad G = KX, \quad W = U^{-1}, \tag{67}$$

$$Y = hT^{-1}, \quad R = h^{-1}Q^{-1}, \quad H = LP, \tag{68}$$

Now, by pre & post multiplying (61), (62) and (43) respectively by *diag{X,Y,I,I,I,I,I,I}*, *diag{I,I,R}* and *W* after using Schur complement (19), (20) and (21) are obtained, which completes the proof.

Remark 1: Note that, obtaining γ which solves the robust stability and performance condition implies the LMI equations reaching large matrices *K* and *L*, so two LMI constraints are added to reduce the norms of *P* and *X*:

$$X - \mu_1 I > 0 \tag{69}$$

$$P - \mu_2 I > 0 \tag{70}$$

Therefore maximization of μ_1 and μ_2 will maximize *X* and *P* which results in minimizing *K* and *L*.

Remark 2: It is obvious from the equations (24) and (33) the term γ^{-1} is a nonlinear constraint, hence, a new variable $\nu = \gamma^{-1}$ is defined and its maximization results in the minimization of γ. Note that considering $\nu > a$ results in $0<\gamma<a$.

Remark 3: The matrix given in (31) is nonlinear because of the term K^TK. This nonlinearity can be eliminated if the following inequality holds ([14]):

$$K^T K < \alpha X^{-1} \quad (71)$$

$$X^{-1} < I \quad (72)$$

V. Simulation Results

The tracking of force and position was evaluated on the nonlinear model of the teleoperation system with proposed controller. The response of the system is studied for two cases, first by applying the observer-based controller suggested in [14] and second by applying the proposed controller. Time delay was considered to be 300ms. The system is subjected to bounded disturbances and measurement noises. All scale factors were unit. The LMIs were solved by CVX toolbox with sdp3 solver [22]. The resulting performance measure was γ=0.011.

In Fig. 2, the responses of the system with observer-based controller [14] are shown. Since, with this controller no performance measure is guaranteed, the tracking of force and position should not be acceptable. Simulation results prove this fact. In Fig. 3, the responses of the system with proposed controller are plotted. The positions of master and slave track each other in soft and rigid environments with high accuracy. It should be noted that there is a small initial error when the environment changes from soft to rigid instead of violating the stability criterion. As it is obvious from the middle part of the figure when the slave robot is in the rigid environment, the position of the master robot should not be changed. Another interesting result is the force behavior. Although additional white noise is added to the slave force output in the simulation, the force tracking is accurate.

VI. Experimental Results

The experimental setup used in this paper consists of two 2-DOF robots as shown in Fig. 4. The master is a “Microsoft Sidewinder Force Feedback 2 Joystick”. The slave robot is made by authors powered by high current 12^v military DC motors and equipped with force sensors that measure the environment forces in 2 degrees of freedom. The control system runs on a PC platform with Advantech PCL-818 and PCL-726 DAS cards. The control code is implemented using Matlab Real-Time workshop and xPC Target Toolbox. Since, the master robot is not equipped with force sensors; its force was estimated using method proposed in [23]. Other settings were exactly the same as mentioned in the simulation.

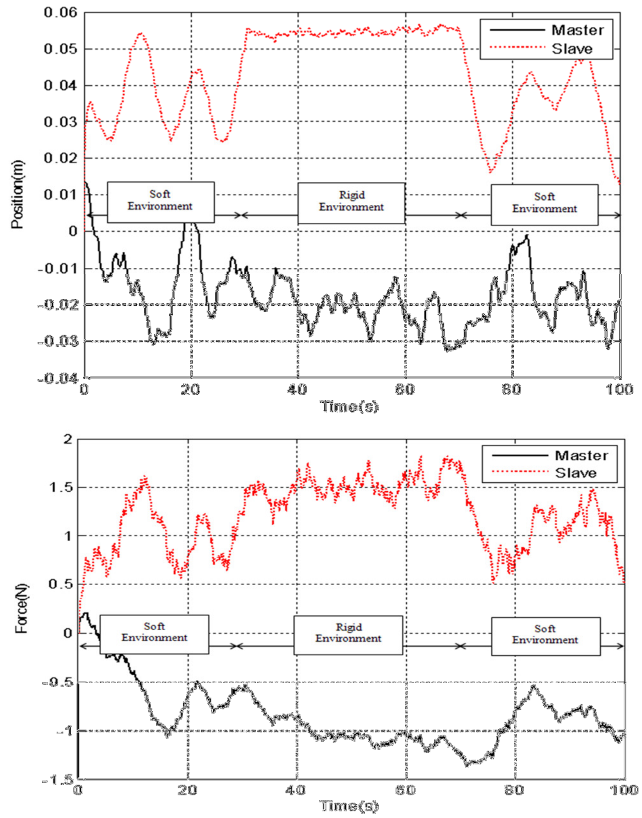

Fig. 2. The position and force tracking for the method proposed in [14].

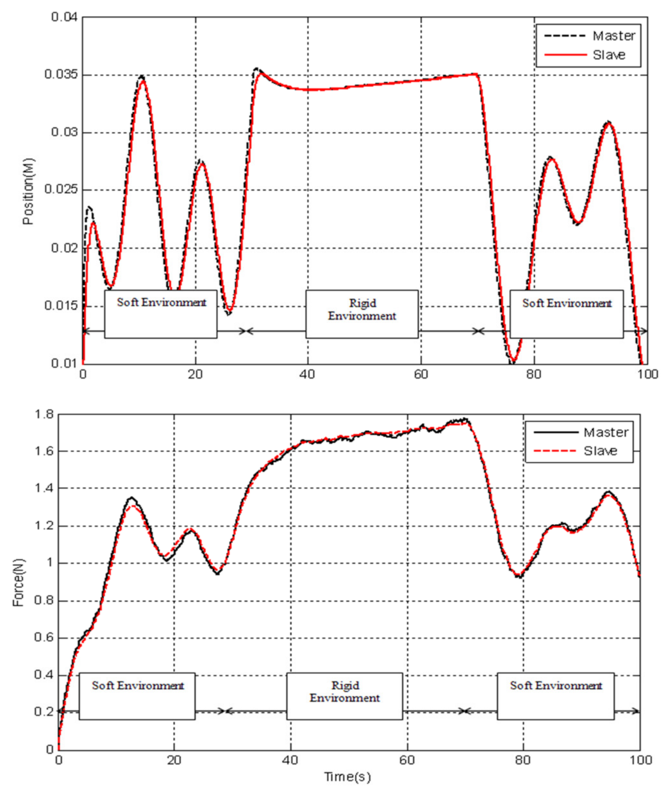

Fig. 3. The position and force tracking for our proposed method

Fig. 4. Master and Slave sides used in practical experiment, the left picture shows the master side and the right picture shows the slave.

Fig. 5 shows the experimental results of the system. As in the previous case, the experiment is established for soft and rigid environments. In both of them the position and force tracking is satisfactory. Also the transitions between two environments are stable.

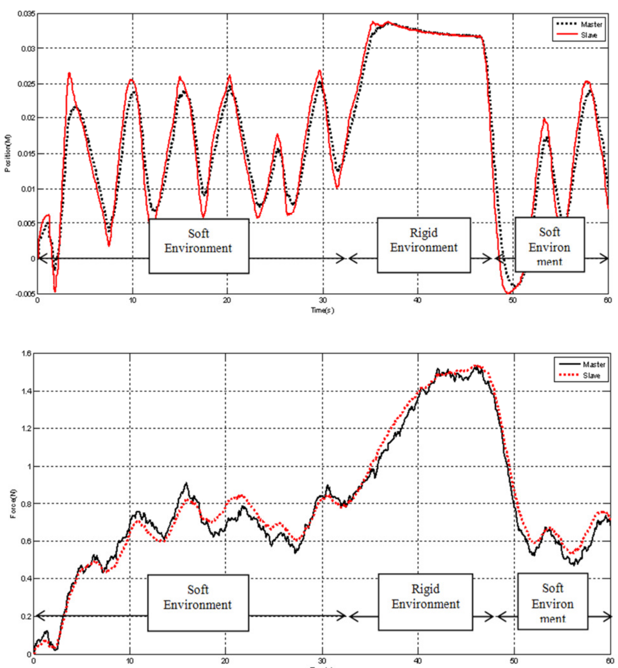

Fig. 5.Experimental results for the proposed method.

VII. Conclusions

In this paper a method for achieving stability and transparency in teleoperation systems under time-delay and uncertainty was proposed. Through the use of adaptive controllers the dynamics of master and slave were linearized. Then an observer-based controller by using LMI was designed to deal with time-delay and uncertainty of the system. Through numerical and experimental results, it was demonstrated that the proposed approach is quite effective for time-delay teleoperation control in the sense of stability and transparency.

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