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Adaptive Control for Force-Reflecting Dual User Teleoperation Systems

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***Abstract*—The aim of this paper is to develop an adaptive force reflection control scheme for dual master nonlinear teleoperation systems. Having a sense of contact forces is very important in applications of dual master teleopreation systems such as surgery training. However, most of the previous studies for dual master nonlinear teleoperation systems are limited in the stability analysis of force reflection control schemes. In this paper, it is assumed that the teleopreation system consists of two masters and a single slave manipulator. In addition, all communication channels are subject to unknown time delays. First, adaptive controllers are developed for each manipulator. Next, Input-to-State Stability (ISS) approach is used to analyze the stability of the closed loop system. Through simulation results, it is demonstrated that the proposed methodology is effective in a nonlinear teleopreation system.**

***Keywords*— teleoperation system, Dual user, adaptive controller, Input-to-state stability**

I. Introduction

The demand for manipulation of remote objects has made the teleoperation systems attractive in several applications such as space exploration, handling hazardous materials and telesurgery. One of the new applications of these systems, which is considered in this paper, is surgery training. In conventional bilateral teleoperation systems, one operator handles a single master robot in order to perform a task on the remote environment by the use of single slave robot [1]. However, some applications like collaboratively performing a task by two human operators need at least two master robots. Therefore, trilateral or dual user teleoperation systems have recently became an attractive field of research.

Dual user teleoperation systems are used in surgical training in which a trainee learns how to do a specific surgery by utilizing the guidance from a trainer. This work is done by means of two master robots, one for the expert trainer and one for the trainee, and a slave robot to do the surgery. In this application, it is desired for the trainee to have feedback information from the environment, and furthermore, have a sense of forces applied by the trainer. The interactions between these two users and the authority allocation is defined by a parameter called dominance factor.

Several control schemes have been used to ensure the stability of dual user teleoperation systems. An $\mathcal{H}_\infty$ based shared control architecture is proposed in [2] for surgery training. However, an important drawback of the proposed structure is that no kinesthetic feedback is provided for the operators. In order to solve this problem, a six-channel control scheme is proposed in [3] for dual user teleopration system which provides kinesthetic feedback from the environment to the human operators.

On the other hand, several researchers have investigated the stability of dual user teleoperation systems such as [4–8]. An important note is that, most of these studies do not consider nonlinear dynamics or time delay in the communication channels. However, considering both of these issues is necessary in practical applications. In [9], the stability of a nonlinear dual user teleoperation system with time delay is investigated by developing a PD controller. However, the performance of the proposed PD control scheme is not sufficiently suitable specially when the nonlinear behavior of the dynamic equations are dominant.

In most of the practical situations, the exact dynamic models of the systems are not available and may vary due to lots of reasons such as aging. In order to addresse the dynamic uncertainty problem of the teleoperation systems, an adaptive approach is presented in this paper. For bilateral teleoperation systems, some researchers have already studied the problem of dynamic uncertainty and some adaptive control algorithms have been previously proposed. For instance, an adaptive passivity-based control method is suggested in [10] which aims at position synchronization of the master and slave manipulators. However, as shown in [11], the method proposed in [10] suffers from not being general and being applicable in the absence of gravity forces. In order to overcome this problem, another adaptive architecture is proposed in [11]. Inspired by [11], an adaptive control scheme for dual user teleoperation is presented in [12] which ensures position tracking. However, the proposed scheme is a position error-based control architecture in which no force is reflected from the environment to the operators. However, in surgery training application, force reflection is essentially needed.

The aim of this paper is to propose an adaptive force-reflecting control structure for dual user teleoperation systems under dynamic uncertainties and unknown communication delays. Motivated by [13], an adaptive control scheme is proposed for dual user teleoperation systems. The present work is mostly an extension of [13] to the case of dual user teleoperation system. As far as we know, no adaptive force-reflecting control scheme has been proposed for dual-master nonlinear teleoperation.

The rest of the paper is organized as follows. In section II, the configuration of dual user teleoperation systems is illustrated and the desired references for these systems are defined. An adaptive control architecture is designed in section III to ensure the stability of the system. In section IV the stability of the overall system is proved. Simulation results are presented in V. Finally, the paper ends up with conclusion and future works in section VI.

II. System Description And Desired References

As stated before, dual user teleoperation systems consists of two users with two master manipulators that carry out the task on the environment by means of a slave manipulator. Each manipulator is connected to the other one through a communication channel. The time delay in the communication channels may cause the instability of the closed loop system. In application of surgery training, a trainer guides a trainee, according to his/her level of expertise, to do a surgery. The desired objective for the trainee is to feel the trainer command and also to have a sense of the environment. Different levels of authority are needed in different situations and it can be adjusted by a parameter called dominance factor.

A. System Dynamics

Each master and slave robot has the following n-DOF nonlinear dynamics [14]

$$\begin{aligned} M_{m1}(q_{m1})\ddot{q}_{m1}+&C_{m1}(q_{m1},\dot{q}_{m1})\dot{q}_{m1}+G_{m1}(q_{m1}) \\ &= u_{ex_{m1}}+u_{m1} \end{aligned} \tag{1}$$

$$\begin{aligned} M_{m2}(q_{m2})\ddot{q}_{m2}+&C_{m2}(q_{m2},\dot{q}_{m2})\dot{q}_{m2}+G_{m2}(q_{m2}) \\ &= u_{ex_{m2}}+u_{m2} \end{aligned} \tag{2}$$

$$\begin{aligned} M_{s}(q_{s})\ddot{q}_{s}+&C_{s}(q_{s},\dot{q}_{s})\dot{q}_{s}+G_{s}(q_{s}) \\ &= u_{ex_{s}}+u_{s} \end{aligned} \tag{3}$$

in which, $q_i \in R^{n\times 1}$ are the vectors of joint variables, where $i = m1$ and $i = m2$ represent for primary and secondary masters, respectively, and $i = s$ for the slave. $M_i(q_i) \in R^{n\times n}$ are the inertia matrices of masters and slave, $C_i(q_i, \dot{q}_i) \in R^{n\times n}$ are the centrifugal and Coriolis matrices, $G_i(q_i) \in R^{n\times 1}$ are the gravity vectors, τ_i are the control inputs, and τ_{ex_i} are the external torques applied to each robots which are described by the following equations:

$$u_{ex_{m1}} = J_{m1}^T(F_{h1}+F_{rm1}) \tag{4}$$

$$u_{ex_{m2}} = J_{m2}^T(F_{h2}+F_{rm2}) \tag{5}$$

$$u_{ex_{s}} = J_{s}^T F_e \tag{6}$$

in these equations J_i denote jacobian of the each manipulators, F_{hi} denote human inserted forces, F_e denotes the environment force and F_{ri} denote the desired forces sent back to the masters. For the rest of the paper, the environment forces are assumed to be bounded and satisfy the following inequality:

$$|F_e| \leq k_1|\dot{q}_s| + k_2|q_s| + |f_e| \tag{7}$$

where f_e is the bounded part of the environment force and can be chosen arbitrarily, while k_1 and k_2 are positive constants. The above inequality can be rewritten in terms of environment torque,

$$|u_{exs}| \leq k_{e1}|\dot{q}_s| + k_{e2}|q_s| + k_{e3}|f_e| \tag{8}$$

where $k_{e1} = J^T k_1$, $k_{e2} = J^T k_2$, and $k_{e3} = J^T$. We also consider that the dynamics equations (1)-(3), satisfy the following properties [14]:

- P1 The inertia matrix is symmetric and positive definite and $M_i^T = M_i$.
- P2 $\forall x \in R^n, x^T(\dot{M}_i(q_i) - 2C_i(q_i,\dot{q}_i))x = 0$.
- P3 Dynamic of the manipulators satisfy the linear parameterization property, i.e. $M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i) + G_i(q_i) = Y_i(q_i,\dot{q}_i,\ddot{q}_i)\theta_i$ where Y_i is the regressor and θ_i is the vector of manipulator parameters.

B. Desired References

In order to meet the control objective discussed before, reference forces and reference position sent to each side are defined as follows, [9]:

$$F_{rm1} = \alpha_1\hat{F}_{h2} + (1-\alpha_1)\hat{F}_{e1} \tag{9}$$

$$F_{rm2} = \alpha_2\hat{F}_{h1} + (1-\alpha_2)\hat{F}_{e2} \tag{10}$$

$$q_{rs} = \alpha_3\hat{q}_{m1} + (1-\alpha_3)\hat{q}_{m2} \tag{11}$$

where $0 \leq \alpha_i \leq 1$ are dominance factors which determine the authority of the dominant side. Besides, $\hat{F}_{e1}$ and $\hat{F}_{e2}$ are the measurement of the environment force transmitted to the first and secondary masters through communication channels, respectively. In addition, $\hat{F}_{hi}$ are the human forces of one master manipulator transferred to the other master. Similar to transmitted forces, $\hat{q}_i$ are the measured position signals sent back to the slave side through communication channels.

III. Adaptive Controller Design

According to the dynamic model of the systems and using P3, the following equations hold for master manipulator

$$\begin{aligned} -M_{mi}(q_{mi})\lambda_{mi}\dot{q}_{mi} - C_{mi}(q_{mi},\dot{q}_{mi})\lambda_{mi}q_{mi} + ... \\ G_{mi}(q_{mi}) = Y_{mi}(\dot{q}_{mi},q_{mi})\theta_{mi} \end{aligned} \tag{12}$$

where $Y_{mi}(\dot{q}_{mi},q_{mi})$ are the master manipulator regressors, θ_{mi} are the vector of master parameters, and λ_{mi} are symmetric positive definite matrices for $i = 1,2$. Denote $i = 1,2$ as the subscript of primary and secondary master parameters, respectively. Likewise, the above equation may be rewritten for the slave manipulator as following.

$$\begin{aligned} -M_s(q_s)\lambda_s\dot{\tilde{q}}_s - C_s(q_s,\dot{q}_s)\lambda_s\tilde{q}_s + G_s(q_s) \\ = Y_s(\dot{q}_s,q_s,\dot{\tilde{q}}_s,\tilde{q}_s)\theta_s \end{aligned} \tag{13}$$

where $Y_s(\dot{q}_s, q_s, \dot{\tilde{q}}_s, \tilde{q}_s)$ is the slave manipulator regressor, θ_s is the vector of slave parameters, λ_s is a symmetric positive definite matrix, and $\dot{\tilde{q}}_s, \tilde{q}_s \in R^{n\times 1}$ represent slave velocity error and slave position error, respectively, defined as:

$$\tilde{q}_s = q_s - q_{rs} \tag{14}$$

$$\dot{\tilde{q}}_s = \dot{q}_s - \dot{q}_{rs} \tag{15}$$

Considering the above definitions, adaptive control laws for master and slave manipulators may be expressed for $t \geq 0$:

$$u_{mi} = Y_{mi}(\dot{q}_{mi}, q_{mi})\hat{\theta}_{mi} - B_{mi}s_{mi} \tag{16}$$

$$u_s = Y_s(\dot{q}_s, q_s, \dot{\tilde{q}}_s, \tilde{q}_s)\hat{\theta}_s - B_s s_s \tag{17}$$

where B_{mi}, B_s are symmetric positive definite matrices, θ_{mi}, θ_s represent for the vector of estimated parameters and s_{mi}, s_s are defined as the following

$$s_{mi} = \dot{q}_{mi} - \lambda_{mi} q_{mi} \tag{18}$$

$$s_s = \dot{q}_s - \lambda_s \tilde{q}_s \tag{19}$$

Subsequently, the adaptation laws for estimated parameters for $t \geq 0$ are:

$$\dot{\hat{\theta}}_{mi} = -\Psi_{mi} Y_{mi}^T(\dot{q}_{mi}, q_{mi}) s_{mi} - \delta_{mi}(\hat{\theta}_{mi} - \theta_{nmi}) \tag{20}$$

$$\dot{\hat{\theta}}_s = -\Psi_s Y_s^T(\dot{q}_s, q_s) s_s - \delta_s(\hat{\theta}_s - \theta_{ns}) \tag{21}$$

where $\theta_{nmi}, \theta_{ns}$ are the vectors of nominal values of parameters, Ψ_{mi}, Ψ_s are symmetric positive definite matrices, and δ_{mi}, δ_s are positive constants. Also, assume $\tilde{\theta}_{mi}$ and $\tilde{\theta}_s$ to be the error between the actual and estimated values of the parameters that are defined as $\tilde{\theta}_{mi} = \hat{\theta}_{mi} - \theta_{mi}, \tilde{\theta}_s = \hat{\theta}_s - \theta_s$, respectively.

IV. Stability Analysis

In this section the stability of dual master teleoperation system, including two master robots and a slave robot with unknown communication delays, is investigated. Similar to the approach proposed in [13], we show the stability of overall system by checking the stability of each subsystems. Fig. 1 shows the overall dual user teleoperation system and its subsystems. First, consider each robot as an individual subsystem. According to the following propositions, we illustrate that the proposed algorithm stabilizes these subsystems. Next, assuming an integrated subsystem including two masters, ISS stability can be easily checked on the new subsystem. Finally, we define the closed-loop system as the feedback interconnection between two masters, as a subsystem, and a slave. Applying the small gain theorem [13], it can be shown that the whole telerobotic system is input-to-state stable.

Inspired by [13], first we investigate the stability of both master subsystems using the proposition below. Denote $\bar{\theta}_{nmi} = \theta_{mi} - \theta_{nmi}$ and $\lambda_{min}(A)$ as the minimum eigenvalue of matrix A.

Proposition 1. Consider the primary and secondary master subsystems (1), (2), and (16), with states $x_{mi} := (q_{mi}^T, \dot{q}_{mi}^T, \tilde{\theta}_{nmi}^T)^T$, inputs F_{h1}, F_{h2}, $\hat{F}_{ei}$, and $\bar{\theta}_{nmi}$. For $\lambda_{min}(B_{mi}) \geq b_{mi} \geq 0$ and $\lambda_{min}(\Psi_{mi}) \geq \psi_{mi} \geq 0$, the closed-loop primary and secondary masters are ISS.

Proof. First we show that the primary master subsystem is ISS. Let us define the ISS-Lyapunov function candidate as:

$$V_{m1} = \frac{1}{2}s_{m1}^T M_{m1}(q_{m1}) s_{m1} + \frac{1}{2}q_{m1}^T q_{m1}^T + \frac{1}{2}\tilde{\theta}_{m1}^T \Psi_{m1}^{-1}\tilde{\theta}_{m1}. \tag{22}$$

It may be easily shown that this function is positive definite, and furthermore, $\underline{\alpha}_{m1}(|x_{m1})| \leq V_{m1} \leq \overline{\alpha}_{m1}(|x_{m1}|)$ for some $\overline{\alpha}_{m1}, \underline{\alpha}_{m1} \geq 0$. Differentiate the given Lyapunov candidate along the trajectories of the system and considering P2:

$$\begin{aligned} \dot{V}_{m1} \;\; = \;\; & -s_{m1}^T B_{m1} s_{m1} - q_{m1}^T \lambda_{m1} q_{m1} \\ & -\delta_{m1}\tilde{\theta}_{m1}^T \Psi_{m1}^{-1}\bar{\theta}_{nm1} - \delta_{m1}\tilde{\theta}_{m1}^T \Psi_{m1}^{-1}\tilde{\theta}_{m1} \\ & +s_{m1}^T u_{exm1} + q_{m1}^T s_{m1} \end{aligned}$$

Employing Young's inequality, the time derivative of V_{m1} is limited to the following upper bound:

$$\begin{aligned} \dot{V}_{m1} \leq (-\lambda_{min}(B_{m1}) + \frac{c_1}{2} + \frac{1}{2c_2})|s_{m1}|^2 + \\ (\delta_{m1}\lambda_{min}(\Psi_{m1}^{-1}) - \frac{1}{2}\delta_{m1}c_3\lambda_{min}^2(\Psi_{m1}^{-1}))|\tilde{\theta}_{m1}|^2 + \\ (-\lambda_{min}(\lambda_{m1}) + \frac{c_2}{2})|q_{m1}|^2 + \frac{|u_{exm1}|^2}{2c_1} + \frac{|\bar{\theta}_{mn}|^2}{2c_3} \end{aligned} \tag{23}$$

where c_i are positive constants. Considering the approach presented in [15], it can be shown that by choosing appropriate values for c_1, c_2, and c_3, master 1 subsystem is ISS with γ_{m1} ISS gain. If we use the same approach for the second master subsystem, it is easy to prove that master 2 subsystem is also ISS with γ_{m2} ISS gain. Let us consider a new integrated subsystem including two masters (see Fig.1). Based on the result of proposition 1, we can show that the integrated subsystem is ISS, as follows.

Proposition 2. Consider the integrated master subsystem, including two masters (1), (2) and (16), with states

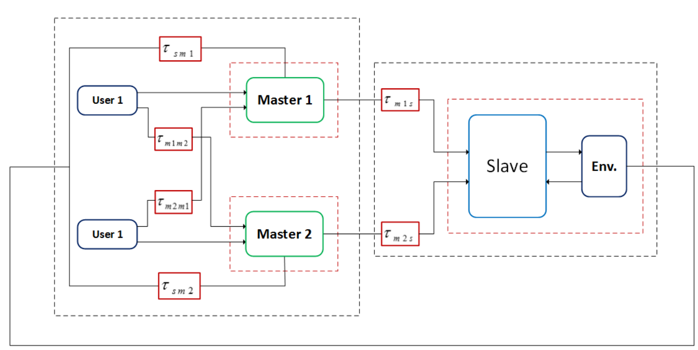

Fig. 1: A dual user teleoperation system

$x_m := (q_{m1}^T, \dot{q}_{m1}^T, \tilde{\theta}_{m1}^T, q_{m2}^T, \dot{q}_{m2}^T, \tilde{\theta}_{m2}^T)^T$, inputs $F_{h1}, F_{h2}, \hat{F}_e, \bar{\theta}_{nm1}$ and $\bar{\theta}_{nm2}$. For $\lambda_{min}(B_{m1}) \geq b_{m1} \geq 0$, $\lambda_{min}(B_{m2}) \geq b_{m2} \geq 0$, $\lambda_{min}(\Psi_{m1}) \geq \psi_{m1} \geq 0$, and $\lambda_{min}(\Psi_{m2}) \geq \psi_{m2} \geq 0$, the closed-loop integrated master is ISS.

Proof. Suppose the ISS-Lyapunov function candidate $V_m = V_{m1} + V_{m2}$. Using the same approach for proposition 1, we simply get the result of proposition 2. Then the integrated master subsystem is ISS with γ_m ISS gain.

As there exist unknown delay in communication channels, we should consider "integrated master system and input delay" as a new subsystem in order to use small gain theorem and prove that the overall system is stable. Employing the result of [13] and utilizing the following lemma, we may state the stability of this subsystem.

Lemma 1. [13] Consider the general system defined by the following differential equation:

$$\dot{x}(t) = F(x(t), u(t)) \tag{24}$$

If the above system is ISS with ISS gain γ, then the new system with delay in input

$$\dot{x}(t) = F(x(t), u(t-\tau)) \tag{25}$$

is also ISS with ISS gain γ for any $T \geq \tau$.

Since there are different delays in inputs, like τ_{sm1} in $\hat{F}_{e1}$ and τ_{m2m1} in $\hat{F}_{h2}$, we should consider the maximum delay input as

$$\tau_m = \max(\tau_{m1m2}, \tau_{m2m1}, \tau_{sm1}\tau_{sm2}) \tag{26}$$

in which, τ_{m1m2}, τ_{m2m1}, τ_{sm1}, and τ_{sm2} are the communication delay between master 1 - master 2, master 2 - master 1, slave - master 1, and slave - master 2, respectively. Then, according to Lemma 1 the new subsystem plus input delay is ISS, as well.

Similar to each master subsystems, we examine the stability of the slave subsystem, the interconnection of the slave robot and the environment, utilizing the proposition below.

Proposition 3. Consider the slave subsystem, (3) and (17), interconnection of slave and environment, with state $x_s := (\tilde{q}_s^T, \dot{q}_s^T, \theta_s^T)^T$, inputs $f_e, \hat{q}_{m1}, \hat{\dot{q}}_{m1}, \hat{q}_{m2}, \hat{\dot{q}}_{m2}$ and θ_{ns}. Then, for $\lambda_{min}(B_s) \geq b_s \geq 0$ and $\lambda_{min}(\Psi_s) \geq \psi_s \geq 0$, the closed loop slave subsystem is ISS.

Proof. The ISS-Lyapunov function candidate for this subsystem may be chosen as

$$V_s = \frac{1}{2} s_s^T M_s(q_s) s_s + \frac{1}{2}\tilde{q}_s^T \tilde{q}_s^T + \frac{1}{2}\tilde{\theta}_s^T \Psi_s^{-1} \tilde{\theta}_s. \tag{27}$$

One can easily check the positive definiteness of this function, and the following inequality $\underline{\alpha}_s(|x_s)| \leq V_s \leq \overline{\alpha}_s(|x_s|)$ for some $\overline{\alpha}_s, \underline{\alpha}_s \geq 0$. Considering assumption 1 and following the approach used in the proof of proposition 1, it can be concluded that the time derivative of V_s along the trajectories satisfies:

$$\dot{V}_s \leq -c_{s1}|s_s|^2 - c_{s2}|\tilde{\theta}_s|^2 - c_{s3}|\tilde{q}_s|^2 + c_{s4}|f_e|^2 + c_{s5}|\hat{q}_{m1}|^2 + c_{s6}|\hat{q}_{m2}|^2 + c_{s7}|\hat{\dot{q}}_{m1}|^2 + c_{s8}|\hat{\dot{q}}_{m2}|^2 \tag{28}$$

where $c_{sj} \geq 0$ for $j = 1, 2, ..., 8$ are constant. Hence, the input-to-state stability of slave subsystem is proven. Using lemma 1, the slave plus input delay subsystem is ISS, as well.

Now, assume the overall system as the feedback interconnection of integrated master and slave subsystems. Combining the results of proposition 3 and pursuing the same trend, the following theorem is stated to show the input-to-state stability of the dual user teleoperation system.

Theorem: Consider the force reflecting dual master teleoperation system (1)-(3), (16)-(17) with state variables $x := (q_{m1}^T, \dot{q}_{m1}^T, \tilde{\theta}_{m1}^T, q_{m2}^T, \dot{q}_{m2}^T, \tilde{\theta}_{m2}, \tilde{q}_s^T, \dot{q}_s^T, \tilde{\theta}_s^T)$, $U = (F_{h1}, F_{h2}, f_e)^T$ as input, and the following output $y := (q_{m1}^T, \dot{q}_{m1}^T, q_{m2}^T, \dot{q}_{m2}^T, \tilde{q}_s^T, \dot{q}_s^T)^T$. Also, assume that the environment forces satisfy (7). Then, the overall system is ISS if there exist $b_{m1}, b_{m2}, b_s, \psi_{m1}, \psi_{m2}, \psi_s > 0$ such that $\lambda_{min}(B_{m1}) \geq b_{m1}, \lambda_{min}(B_{m2}) \geq b_{m2}, \lambda_{min}(B_s) \geq b_s, \lambda_{min}(\Psi_{m1}) \geq \psi_{m1}, \lambda_{min}(\Psi_{m2}) \geq \psi_{m2}, \lambda_{min}(\Psi_s) \geq \psi_s$.

Proof: The proposed ISS small gain theorem in [13] is used to complete proof of the overall system stability. Let us denote the ISS gain of the closed-loop integrated master and input delay subsystem as γ_m, from the input F_e to the output $y = (q_{m1}, \dot{q}_{m1}, q_{m2}, \dot{q}_{m2})$. Also, consider γ_s as the ISS gain of closed-loop slave and input delay subsystem, from the input $u = (q_{m1}, \dot{q}_{m1}, q_{m2}, \dot{q}_{m2})$ to the output $y = (q_s, \dot{q}_s)$. Then, it can be stated that the overall dual user teleoperation system is ISS if

$$\gamma_m \cdot \gamma_s \cdot \gamma_e < 1 \tag{29}$$

where $\gamma_e = max(k_1, k_2)$, and k_1 and k_2 are positive constants defined in eq. (7). As we can choose the ISS gains subject to f_e, so as the above inequality may always be satisfied. Hence, the proof is complete.

V. Simulation Results

In this section, the simulation results are presented to demonstrate the practical use of the proposed algorithm. The experiment is conducted on three identical two-link planar arms [14]. The system dynamics are described by (1)-(3), and we considered that $M_{m1} = M_{m2} = M_s$, $C_{m1} = C_{m2} = C_s$, and $G_{m1} = G_{m2} = G_s$. The elements of inertia, Corolios, and gravity matrices are defined as:

$$\begin{aligned}
&M_{11}(q) = m_1 l_{c1}^2 + m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2}\cos(q_2)) + I_1 + I_2 \\
&M_{12}(q) = M_{21}(q) = m_2 l_{c2}^2 + m_2 l_1 l_{c2}\cos(q_2) + I_2 \\
&M_{22} = m_2 l_{c2}^2 + I_2 \\
&C_{11}(q,\dot{q}) = -m_2 l_1 l_{c2}\sin(q_2)\dot{q}_2 \\
&C_{12}(q,\dot{q}) = -m_2 l_1 l_{c2}\sin(q_2)(\dot{q}_1 + \dot{q}_2) \\
&C_{21}(q,\dot{q}) = -m_2 l_1 l_{c2}\sin(q_2)\dot{q}_1 \\
&C_{22}(q,\dot{q}) = 0 \\
&G_1(q) = g\cos(q_1)(m_1 l_{c1} + m_2 l_1) + m_2 l_{c2} g\cos(q_1 + q_2) \\
&G_2(q) = m_2 l_{c2} g\cos(q_1 + q_2)
\end{aligned}$$

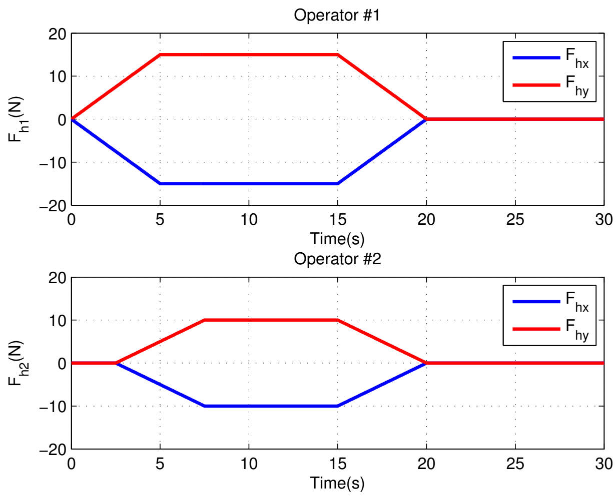

Fig. 2: Operators applied forces

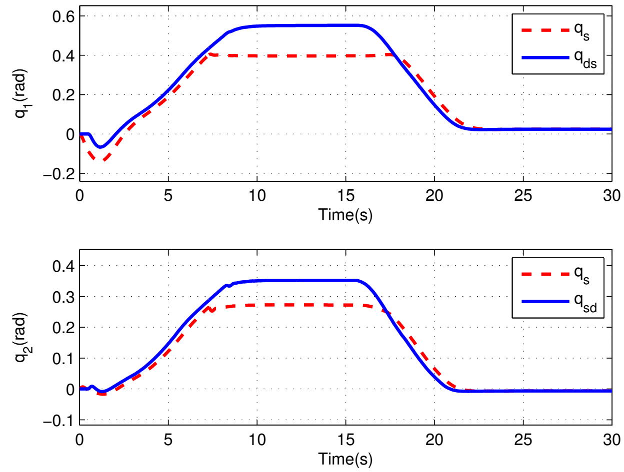

Fig. 4: Desired and actual values of the slave position

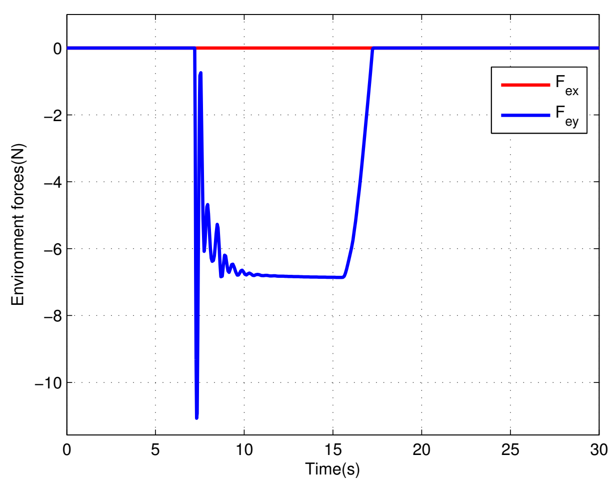

Fig. 3: Environment forces applied to the slave

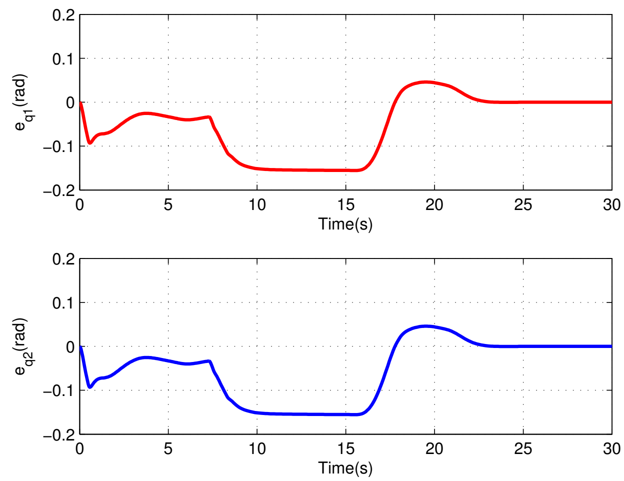

Fig. 5: Position tracking error of the slave manipulator

where, the nominal values of the parameters are $m_1 = 10\,kg, l_1 = 1\,m, l_{c1} = 0.5\,m, I_1 = \frac{10}{12}\,kgm^2, m_2 = 5\,kg, l_2 = 1\,m, l_{c2} = 0.5\,m, I_2 = \frac{5}{12}\,kgm^2$, and $g = 9.8\,m/s^2$. From property P3, the vector of manipulator parameters may be expressed by

$$\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \end{bmatrix} = \begin{bmatrix} m_1 l_{c1}^2 + m_2 l_1^2 + I_1 \\ m_2 l_{c2}^2 + I_2 \\ m_2 l_1 l_{c2} \\ m_1 l_{c1} \\ m_2 l_1 \\ m_2 l_{c2} \end{bmatrix}$$

Furthermore, the control parameters in (12)-(21) are defined as: $\lambda_{mi} = 5I$, $B_{mi} = 10I$, $\Psi_{mi} = 0.1I$, $\delta_{mi} = 2.5$, $\lambda_s = 2.5I$, $B_s = 20I$, $\Psi_s = 0.1I$, and $\delta_s = 2.5$. Here, I is assumed to be the identity 2×2 matrix. The simulation has been performed for zero initial conditions and all the communication channels' delays are considered $0.5s$. Besides, all the dominance factors, α_1, α_2, and α_3 are set to 0.5. Suppose that the slave robot is in contact with a stiff environment at the surface $y = 1$. The environment is modeled by a spring-damper system as follows:

$$F_{ey} = \begin{cases} -B\dot{y} - Ky & \text{if } y \geq 1 \\ 0 & \text{otherwise} \end{cases}$$

where $K = 1000$ and $B = 1$. It is considered that the environment exerts forces just in the y-direction and the contact forces on x-direction are equal to zero. In order to examine the stability of the proposed method under dynamic uncertainty, we assume the actual mass of the first link of the master 1 manipulator as $m_1 = 9kg$. While its nominal value is still considered as $m_1 = 10kg$.

Simulation results are depicted in Figs. 2-6. Fig. 2 shows the operator exerted forces. Assume that each operator exerts different forces to the master console on his/her side independent of the other operator. Due to the applied forces by the operators, the slave robot follows a certain trajectory and contacts the environment. The reflecting contact forces are shown in Fig. 3. Besides, Fig. 4 demonstrate the slave joint angles and their desired references and Fig. 5 shows the position tracking errors. Finally, Fig.6 displays the estimated value for master 1 manipulator as an example. As we can see in this figure, the estimated values of the manipulator parameters converge to constant values.

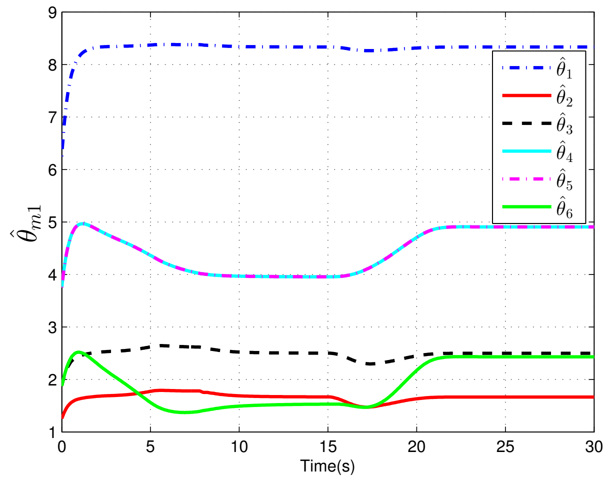

Fig. 6: Estimated parameters of the slave manipulator

As it is shown in Fig.3, the slave robot moves in free space and it follows the desired trajectory defined by both masters joint angles with small position errors. Around the time $7.5s$ the slave contacts the obstacle and environment forces send back to the masters side. During the time $7.5s$ and $17s$, the slave is in contact with the environment and we have the environment and operators' forces at the same time. In Fig. 6, it can be seen that after few seconds the slave end-effector goes to a stable position. However, due to the contact forces we have more tracking errors, compared to that of free motion. After the time $17s$, the slave contact to the environment is released and it moves freely in space again. We still have non-zero human forces till the time $20s$ and after that each robots goes to his stable desired position, $q_i(0) = 0$. Based on the experiment, it can be concluded that the overall system is stable even when it is in contact with a rigid environment. Therefore, the suggested control algorithm ensures stability of the system.

VI. Conclusions

In this paper, an adaptive force reflection control scheme is proposed for dual master teleoperation systems. All of the subsystems are supposed to be nonlinear and all communication channels are subject to time delay. The stability of the closed-loop system is investigated using the ISS approach. Simulation results show the effectiveness of the proposed approach. The proposed control scheme is developed for nonlinear teleoperation with parametric uncertainty and time delay. Our future work is to develop a generalized control scheme which is able to tolerate unstructured uncertainty and variable time delay. In addition, we plan to develop an experimental test bed for surgery training and experimentally evaluate the performance of the proposed approach.

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