An Observer-based Force Reflection Robust Control for Dual User Haptic Surgical Training System

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***Abstract*—This paper investigates the controller design problem for the dual user haptic surgical training system. In this system, the trainer and the trainee are interfaced together through their haptic devices and the surgical operations on the virtual environment is performed by the trainee. The trainer is able to interfere into the procedure in the case that any mistakes is made by the trainee. In the proposed structure, the force of the trainer's hands is reflected to the hands of the trainee to give necessary guidance to the trainee. The force signal is obtained from an unknown input high gain observer. The position of the trainee and the contact force with the environment are sent to the trainer to give him necessary information regarding the status of surgical operations. Stabilizing control laws are also designed for each haptic device and the stability of the closed loop nonlinear system is proven. Simulation results are presented to show the effectiveness of the proposed controller synthesis.**

I. Introduction

Teleoperation systems give human operators the ability to handle remote environments. These systems have received several applications in areas such as space explorations, handling poisonous materials, and robotic surgery. Several control schemes have been proposed for nonlinear single user teleoperation systems based on PD control [1], adaptive control [2], sliding impedance control [3], robust output feedback control [4], decentralized H_∞ control [5], etc. The reader is referred to [6] for a historical review.

A relatively novel area of teleoperation systems is dual user haptic systems in which two users collaboratively perform a task. The most important applications of dual user haptic systems are robotic tele-rehabilitation [7] and surgery training [8]. Until now, several control structures have been proposed for dual user haptic systems based on H_∞ control [9], six-channel control architecture [10], adaptive position control [11], adaptive force reflecting control [12]. However, these investigations have proposed the extended versions of single user teleoperation control methodologies with little consideration of the special and application-based requirements of dual user haptic systems.

Indeed, due to the interaction between the users in the dual-user haptic systems, new application-based control architectures should be developed. For instance, in the surgery training application two different users including a trainer and a trainee collaboratively perform a surgery and it is very beneficial to design control architectures according to the special role of each operator. Apparently, the role of the trainee is to learn the surgical operations, whereas the trainer needs to supervise the operations and avoid undesired complications for the patient. A few investigations have developed such application based control structures for surgery training. As a case in point, in [13] an expertise-oriented training approach is developed for surgery training application in dual user haptic systems. In this approach, the magnitude of the haptic guidance force applied to the hands of the trainee depends on the relative skills. However, the stability analysis is investigated in the simple linear case. In fact, the controller should preserve the stability of the system under various operational conditions, specially nonlinearity of the system's components.

The most remarkable feature of this research is to propose an application-based control structure for the dual user haptic surgical training system. In the suggested control methodology, the hand force of the trainer is reflected to the trainee's hand to give him the necessary haptic cues and guide him along the correct motion trajectory of the surgical operations. The position of the trainee as well as the environment's contact force are transmitted to the trainer's side to offer him necessary information regarding the current status of surgery. To ensure the stability of the system, stabilizing control laws are designed and applied for each haptic device. The stability of the nonlinear system is analyzed using the Input-to-State Stability (ISS) approach. The ISS approach have found several applications in the stability analysis of the force reflecting haptic systems [14], [15]. On the other hand, in order to obtain the hand force of the trainer, an unknown input high gain observer is utilized. High gain observers have been proved to be effective in estimation of unknown states [16],[17] and unknown inputs [18] of nonlinear mechanical systems. The attraction of high gain observers among the researchers is mainly due to their simple structure as well as their robustness against unmodeled dynamics.

The rest of the paper is organized as follows. The proposed control structure is explained in Section II. Section III presents the stability analysis. The simulation results are detailed in Sections IV. Conclusions are stated in Section V.

II. The Proposed Control Structure

A dual user haptic surgical training system allows a novice to learn the surgical skills using the haptic cues from an expert surgeon. As shown in Fig. 1, the system is composed of five components including the trainer, the trainee, the haptic

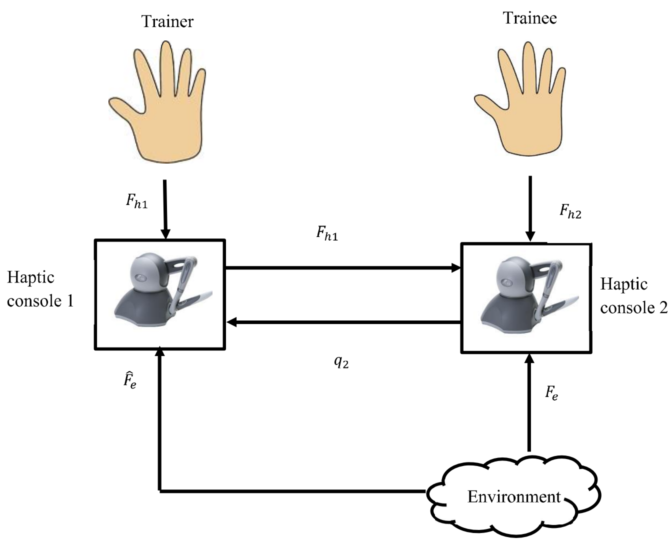


Fig. 1: The haptic system for surgery training.

consoles #1 and #2, and the virtual environment. Through the haptic console #1, the trainer receives concurrently the position of the trainee and the contact force of the environment. This signals help the trainer to have necessary information about the current status of the surgery. The trainer is also able to interfere into the procedure by applying corrective forces in the case that any incorrect movement is caused by the trainee. In this case, the corrective forces applied by the trainer to the haptic console #1 are transmitted to the trainee's hands through the haptic console #2. In this system, the trainee performs the surgical operations on the virtual environment meaning that the force of virtual environment depends on the position signal of the haptic console #2 and its derivatives.

The dynamics of a dual user haptic surgical training system consisting of two n-DOF robot manipulators can be expressed as [19]

$$\begin{aligned} M_1(q_1)\ddot{q}_1 + C_1(q_1,\dot{q}_1)\dot{q}_1 + G_1(q_1) \\ = u_1 + F_{h1} + F_e \end{aligned} \tag{1}$$

$$\begin{aligned} M_2(q_2)\ddot{q}_2 + C_2(q_2,\dot{q}_2)\dot{q}_2 + G_2(q_2) \\ = u_2 + F_{h2} + F_e \end{aligned} \tag{2}$$

where $q_i \in \mathbb{R}^{n\times 1}$ are the joint displacement vectors, $M_i(q_i) \in \mathbb{R}^{n\times n}$ are the inertia matrices, $C_i(\dot{q}_i, q_i)\dot{q}_i \in \mathbb{R}^{n\times n}$ denote the centripetal and Coriolis torques, $G_i(q_i) \in \mathbb{R}^{n\times 1}$ are the vectors of gravitational torques, $u_i \in \mathbb{R}^{n\times 1}$ stands for the control torque vectors, $F_{hi} \in \mathbb{R}^{n\times 1}$ are the forces applied by the surgeons, and $F_e \in \mathbb{R}^{n\times 1}$ is the contact force of environment. Throughout this paper, the subscript i denotes the haptic console #1 for $i = 1$ and haptic console # 2 for $i = 2$.

Let us review some useful properties of the dynamic equations (1), (2) as follows [19]:

Property 1. The inertia matrix $M_i(q_i)$ is symmetric and positive definite for all $q_i \in \mathbb{R}$. In addition, it is shown that,

$$\lambda_m I_{n\times n} \leq M(q) \leq \lambda_M I_{n\times n} \tag{3}$$

Property 2. The matrix $\dot{M}_{ii}(q_i) - 2C(q_i,\dot{q}_i)$ is skew symmetric which means that

$$x^T\big(\dot{M}_i(q_i) - 2C_i(q_i,\dot{q}_i)\big)x = 0 \quad \forall x \in \mathbb{R}^n \tag{4}$$

Property 3. The left hand side of the dynamic models is linear in a set of physical parameters

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = Y_i(q_i,\dot{q}_i,\ddot{q}_i)\theta_i \tag{5}$$

the function, Y is called the regressor and the Θ is the vector of physical parameters.

Next, a control scheme is proposed for the dual user haptic system for the surgery training application. Consider the following control law:

$$\begin{aligned} u_1 =& \hat{M}_1(q_1)\Lambda_1(\dot{q}_2 - \dot{q}_1) + \hat{C}_1(q_1,\dot{q}_1)\Lambda_1(q_2 - q_1) \\ &+ \hat{G}_1(q_1) - K_1(\dot{q}_1 + \Lambda_1(q_1 - q_2)), \end{aligned} \tag{6}$$

$$\begin{aligned} u_2 =& -\hat{M}_2(q_2)\Lambda_2\dot{q}_2 - \hat{C}_2(q_2,\dot{q}_2)\Lambda_2 q_2 \\ &+ \hat{G}_2(q_2) - K_2(\dot{q}_2 + \Lambda_2 q_2) + \hat{F}_{h1}, \end{aligned} \tag{7}$$

where $\Lambda_i \in \mathbb{R}^{n\times n}$ and $K_i \in \mathbb{R}^{n\times n}$ are diagonal positive definite gain matrices and the notation $\hat{(\cdot)}$ represents the nominal or estimated value of $(\cdot)$ that will be explained later for each component. The control law (6) for the haptic console #1 is a position tracker controller that tracks the position of the haptic console #2. By this means, the trainer get necessary information about the current position of the trainee. Besides, the control law (7) for the haptic console #2 is designed based on the objectives on stabilization and force reflection. The stabilizing part ensures the stability of the system, while the force reflecting part applies the trainer's hand force to the trainee's hand to correct the trainee's movements. Note that, the presented control law is a modified version of the well-known passivity-based robust control law [19]. Utilizing Property 3, the control (6) and (7) will reduce to:

$$u_1 = Y_1\hat{\theta}_1 - K_1(\dot{q}_1 + \Lambda_1(q_1 - q_2)), \tag{8}$$

$$u_2 = Y_2\hat{\theta}_2 - K_2(\dot{q}_2 + \Lambda_2 q_2) + \hat{F}_{h1}. \tag{9}$$

Now, define

$$\begin{aligned} r_1 &= \dot{q}_1 + \Lambda_1\tilde{q}, \\ r_2 &= \dot{q}_2 + \Lambda_2 q_2 \end{aligned} \tag{10}$$

where $\tilde{q} = q_1 - q_2$. Then, combine the control laws (8) and (9) with the dynamic equations (1) and (2) and use (10) to have:

$$\begin{aligned} M_1(q_1)\dot{r}_1 + C_1(q_1,\dot{q}_1)r_1 + K_1 r_1 \\ = Y_1(\hat{\theta}_1 - \theta_1) + F_{h1} + F_e \end{aligned} \tag{11}$$

$$\begin{aligned} M_2(q_2)\dot{r}_2 + C_2(q_2,\dot{q}_2)r_2 + K_2 r_2 \\ = Y_2(\hat{\theta}_2 - \theta_2) + \hat{F}_{h1} + F_{h2} + F_e \end{aligned} \tag{12}$$

Next, the terms $\hat{\theta}_i$ for $i = 1, 2$ in (8) and (9) are chosen as

$$\hat{\theta}_i = \theta_i^* + \delta\theta_i \tag{13}$$

where θ_i^* represent the nominal values of θ_i and $\delta\theta_i$ are additional control terms defined as in [19]:

$$\delta\theta_i = \begin{cases} -\xi_i \frac{Y_i^T r_i}{\|Y_i^T r_i\|}, & \|Y_i^T r_i\| > \mu_i \\ -\frac{\xi_i}{\mu_i} Y_i^T r_i, & \|Y_i^T r_i\| \le \mu_i \end{cases} \tag{14}$$

where μ_i are small positive values and ξ_i are the uncertainty bounds such that

$$\|\tilde{\theta}_i\| = \|\theta_i - \theta_i^*\| \le \xi_i. \tag{15}$$

Another issue is to find $\hat{F}_{h1}$ which is the estimated hand force of the trainer. Assume that the state variable vector for the dynamic equation of the haptic console #1 is defined as $[x_1^T \;\; x_2^T]^T = [q_1^T \;\; \dot{q}_1^T]^T$. Then, the state space description of the dynamic equation (2) is given as:

$$\begin{aligned} \dot{x}_1 =& x_2 \\ \dot{x}_2 =& M_1^{-1}(x_1)\big(-C_1(x_1, x_2)x_2 - G_1(x_1) \\ &+ u_2 + F_{h1} + F_e\big) \end{aligned} \tag{16}$$

The hand force of the trainer is estimated by the following high gain observer [16], [17]:

$$\begin{aligned} \dot{\hat{x}}_1 =& \hat{x}_2 + \frac{a_1}{\epsilon}(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 =& \hat{M}_1^{-1}(\hat{x}_1)\big(-\hat{C}_1(\hat{x}_1, \hat{x}_2)\hat{x}_2 - \hat{G}_1(\hat{x}_1) \\ &+ u_2 + F_e\big) + \frac{a_2}{\epsilon^2}(x_1 - \hat{x}_1) \\ \hat{F}_{h1} =& \frac{a_2}{\epsilon^2} M_2(\hat{x}_1)(x_1 - \hat{x}_1) \end{aligned} \tag{17}$$

where ϵ is a sufficiently small positive constant and the positive values a_1 and a_2 are chosen such that the roots of

$$\lambda^2 + a_1\lambda + a_2 = 0$$

are both in the left-half plane.

III. Stability Analysis

The stability of the dual user haptic surgical training system is analyzed in this section. The ISS stability of the haptic console #1 and its unknown input observer are investigated in *Lemma 1* and *Lemma 2*, respectively. Then, the ISS stability of haptic console #2 is verified in *Lemma 3*. Finally, *Theorem 1* presents the stability analysis of the whole haptic surgical training system as the main conclusion of this section.

Lemma 1: The closed loop of the haptic console #1 subsystem is ISS with respect to the state $[q_1^T, \dot{q}_1^T]^T$ and the input $[\xi_1, \dot{q}_2^T, (F_{h1} + F_e)^T]^T$.

Proof: Consider the Lyapunov function candidate

$$V_1 = \frac{1}{2} r_1^T M_1(q_1) r_1 + \tilde{q}^T \Lambda_1 K_1 \tilde{q}. \tag{18}$$

Calculating $\dot{V}_1$ and using *Property 2* yields

$$\begin{aligned} \dot{V}_1 =& r^T M_1(q_1)\dot{r}_1 + \frac{1}{2} r^T \dot{M}_1(q_1) r_1 + 2\tilde{q}^T \Lambda_1 K_1 \dot{\tilde{q}} \\ =& -r_1^T K_1 r_1 + 2\tilde{q}^T \Lambda_1 K_1 \dot{\tilde{q}} \\ &+ \frac{1}{2} r^T \big(\dot{M}_1(q_1) - 2C_1(q_1, \dot{q}_1)\big) r_1 \\ =& -\tilde{q}^T \Lambda_1 K_1 \Lambda_1 \tilde{q} - \dot{q}_1 K_1 \dot{q}_1 + r^T Y(\tilde{\theta} + \delta\theta) \\ &- 2\tilde{q}^T \Lambda_1 K_1 \dot{q}_2 + r^T(F_{h1} + F_e) \end{aligned} \tag{19}$$

Next, using the Young's quadratic inequality leads to

$$\begin{aligned} \dot{V}_1 \le& -\frac{1}{2}\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)\|\tilde{q}\|^2 - \frac{3}{4}\lambda_{\min}(K_1)\|\dot{q}_1\|^2 \\ &+ r^T Y(\tilde{\theta} + \delta\theta) \\ &+ \frac{2\lambda_{\max}(\Lambda_1 K_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)}\|\dot{q}_2\|^2 \\ &+ \big(\frac{\lambda_{\max}(\Lambda_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)} + \frac{1}{\lambda_{\min}(K_1)}\big)\|F_{h1} + F_e\|^2 \end{aligned} \tag{20}$$

Next, define $\eta_1 = Y_1^T r_1$ and using (15) it is concluded that

$$\eta_1^T(\tilde{\theta_1} + \delta\theta_1) \le \eta_1^T(\xi_i \frac{\eta_1}{\|\eta_1\|} + \delta\theta_1) \tag{21}$$

Then, combine (37) and (21) for $\|\eta_1\| > \mu_1$ leads to $\eta_1^T(\tilde{\theta_1} + \delta\theta_1) \le 0$. In the case that $\|\eta_1\| \le \mu_1$, we have

$$\begin{aligned} \eta_1^T(\tilde{\theta_1} + \delta\theta_1) \le& \eta_1^T(\xi_1 \frac{\eta_1}{\|\eta_1\|} - \frac{\xi_1}{\mu_1}\eta_1) \\ =& \xi_1\|\eta_1\| - \frac{\xi_1}{\mu_1}\|\eta_1\|^2 \end{aligned} \tag{22}$$

Note that, the expression $\xi_1\|\eta_1\| - \frac{\xi_1}{\mu_1}\|\eta_1\|^2$ have a maximum value $\mu_1\frac{\xi_1}{2}$ when $\|\eta_1\| = \frac{\mu_1}{2}$. Utilizing this fact the following inequality is extracted from (20):

$$\begin{aligned} \dot{V}_1 \le& -\frac{1}{2}\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)\|\tilde{q}\|^2 - \frac{3}{4}\lambda_{\min}(K_1)\|\dot{q}_1\|^2 \\ &+ \frac{\epsilon}{2}\|\xi_1\| + \frac{2\lambda_{\max}(\Lambda_1 K_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)}\|\dot{q}_2\|^2 \\ &+ \big(\frac{\lambda_{\max}(\Lambda_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)} + \frac{1}{\lambda_{\min}(K_1)}\big)\|F_{h1} + F_e\|^2 \end{aligned} \tag{23}$$

From (18) and (23) the closed loop of the haptic console #1 subsystem is ISS with respect to state $[q_1^T, \dot{q}_1^T]^T$ and the input $[\xi_1, \dot{q}_2^T, (F_{h1} + F_e)^T]^T$. □

Lemma 2: The high gain observer is ISS with respect to the input $[q_1^T, \dot{q}_1^T]^T$ and the observation error as the state variable.

Proof: First, the estimation error is defined as

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \end{bmatrix} \tag{24}$$

Then, the dynamic equation of the estimation error is derived as

$$\dot{e} = Ae + B\Delta - HCe \tag{25}$$

where

$$
\begin{aligned}
A &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \\
C &= \begin{bmatrix} 1 & 0 \end{bmatrix}, H = \begin{bmatrix} \frac{a_1}{\epsilon} \\ \frac{a_2}{\epsilon^2} \end{bmatrix}.
\end{aligned} \tag{26}
$$

In addition, the dynamic uncertainty term Δ is defined as

$$
\begin{aligned}
\Delta =& M_1^{-1}(x_1)\big(-C_1(x_1,x_2)x_2 - G_1(x_1)\big) \\
&- \hat{M}_1^{-1}(\hat{x}_1)\big(-\hat{C}_1(\hat{x}_1,\hat{x}_2)\hat{x}_2 - \hat{G}_1(\hat{x}_1)\big)
\end{aligned} \tag{27}
$$

Then, inspiring from [16], define

$$
\zeta = \begin{bmatrix} 1 & 0 \\ 0 & \epsilon \end{bmatrix} e. \tag{28}
$$

Hence, (25) is equivalent with

$$
\epsilon\dot{\zeta} = A_0\zeta + \epsilon^2 B\Delta \tag{29}
$$

Then, a Lyapunov function candidate is chosen as

$$
V_2 = \zeta^T P \zeta \tag{30}
$$

where P is the solution of the Lyapunov equation $A_0^T P + PA_0 = -Q$ in which Q is a positive definite matrix. Next, the derivative of V_2 is calculated as

$$
\dot{V}_2 = -\epsilon^{-1}\zeta^T Q\zeta + 2\epsilon\zeta^T PB\Delta \tag{31}
$$

On the other hand, due to the Lipschitz condition of the elements of dynamic elements of the robot and using Property 1, it is easy to shown that there exists $l_1 > 0$ and $l_2 > 0$ such that

$$
\Delta \leq l_1\|x\| + l_2\|\zeta\| \tag{32}
$$

By using (32) and we have that

$$
\dot{V}_2 \leq \big(-\epsilon^{-1}\lambda_{\min}(Q) + 2\epsilon l_2\|P\|\big)\|\zeta\|^2 + 2\epsilon l_1\|P\|\|\zeta\|\|x\| \tag{33}
$$

Next, using the Young's quadratic inequality, it can be shown that

$$
\dot{V}_2 \leq \big(-\frac{3}{4}\epsilon^{-1}\lambda_{\min}(Q) + 2\epsilon l_2\|P\|\big)\|\zeta\|^2 + \frac{2\epsilon^2 l_1\|P\|}{\lambda_{\min}(Q)}\|x\|^2 \tag{34}
$$

From (30) and (34), it is proven that the high gain observer is ISS with respect to state ζ and the input $[q_1^T, \dot{q}_1^T]^T$ if the scalar ϵ and the matrix Q are appropriately selected. □

Lemma 3: The closed loop of the haptic console #2 subsystem is Input-to-State Stable (ISS) with respect to the state $[q_2^T, \dot{q}_2^T]^T$ and the input $[\xi_2, \hat{F}_{h1}^T, (F_{h2} + F_e)^T]^T$.

Proof: The following Lyapunov function candidate is considered:

$$
V_3 = \frac{1}{2} r_2^T M_2(q_2) r_2 + q_2^T \Lambda_2 K_2 q_2. \tag{35}
$$

Then, using the same discussion as in the proof of *Lemma 1*, $\dot{V}_3$ is computed as

$$
\begin{aligned}
\dot{V}_3 \leq& -\frac{1}{2}\lambda_{\min}(\Lambda_2 K_2 \Lambda_2)\|q_2\|^2 - \frac{1}{2}\lambda_{\min}(K_2)\|\dot{q}_2\|^2 \\
&+ \frac{\epsilon}{2}\|\xi_2\| + \big(\frac{\lambda_{\max}(\Lambda_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)} + \frac{1}{\lambda_{\min}(K_1)}\big)\|\hat{F}_{h1}\|^2 \\
&+ \big(\frac{\lambda_{\max}(\Lambda_1)}{\lambda_{\min}(\Lambda_1 K_1 \Lambda_1)} + \frac{1}{\lambda_{\min}(K_1)}\big)\|F_{h2} + F_e\|^2
\end{aligned} \tag{36}
$$

From (35) and (36) it is concluded that the closed loop of the haptic console #2 subsystem is ISS with respect to state $[q_2^T, \dot{q}_2^T]^T$ and the input $[\xi_2, \hat{F}_{h1}^T, (F_{h2} + F_e)^T]^T$. □

Theorem 1: Suppose that the force reflecting control scheme (6) and (7) and the observer (17) are applied to the haptic surgical training system (1) and (2). Then the overall system is ISS, provided that the parameters of the control structure are appropriately selected.

Proof: The ISS small gain approach of [14] is utilized in the stability analysis of the overall surgery training haptic system. From *Lemma 1* and *Lemma 2*, the closed loop system of the system composed of the haptic console #1 and the high gain observer is Input-to-Output (IOS) stable with the input $[\xi_1, \dot{q}_2^T, (F_{h1} + F_e)^T]^T$ and output $\hat{F}_{h1}$. Consider that the IOS gain of this system is denoted by γ_1. In addition, *Lemma 3* shows that the haptic console #2 system is IOS with input $[\xi_2, \hat{F}_{h1}^T, (F_{h2} + F_e)^T]^T$ and output $[q_2^T, \dot{q}_2^T]^T$. It is supposed that γ_2 is the IOS gain of the haptic console #2 subsystem. From the small gain theorem, the overall dual user haptic surgical training system is ISS if $\gamma_1\gamma_2 < 1$. Since the ISS gains depend on the parameters K_i, Λ_i, and ϵ it is always possible to preserve the ISS stability of the system with the appropriate selection of the control structure parameters. □

Remark 1: The proposed control structure is based on the assumption that the robots are kinematically similar. If this assumption is not satisfied, it is necessary to resolve the controllers in Cartesian space.

IV. Simulation Results

The proposed observer-based force reflection control scheme is applied to a dual user haptic surgical training system. Two identical 2-DOF robotic manipulators with revolute joints are considered as the haptic console #1 and the haptic console #2. The dynamic relations of such robot in both normal and regressor form is presented in [11]. In the simulations, the physical parameters of the haptic consoles are set as $l_1 = l_2 = 0.1m$, $m_1 = m_2 = 0.1Kg$, and $g = 9.81m/s^2$. In order to investigate the robustness of the control scheme in the presence of parametric uncertainty, all the dynamic parameters of the robots are perturbed by 20% in applying the control laws. Moreover, the control gains of the haptic console #1 are selected as $K_1 = 10\, I_{2\times 2}$, $\Lambda_1 = 20\, I_{2\times 2}$, $\eta_1 = 10^{-4}$, $K_2 = 0.1\, I_{2\times 2}$, $\Lambda_2 = 0.2\, I_{2\times 2}$, $\eta_2 = 0.1$. Note that, the haptic console #1 needs greater values of the control gains and more strict bound of the tracking error than the haptic console

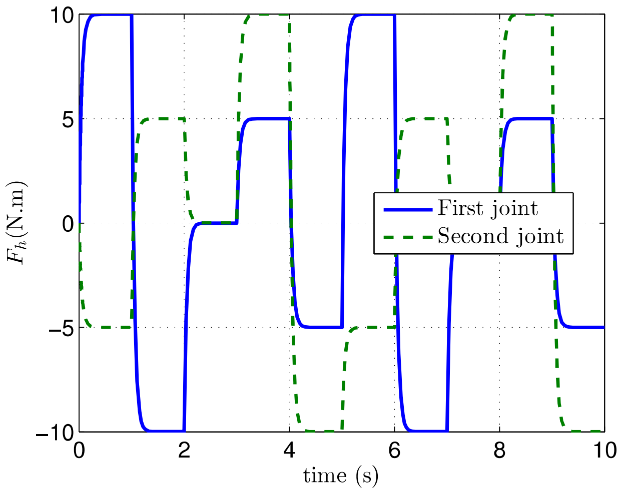
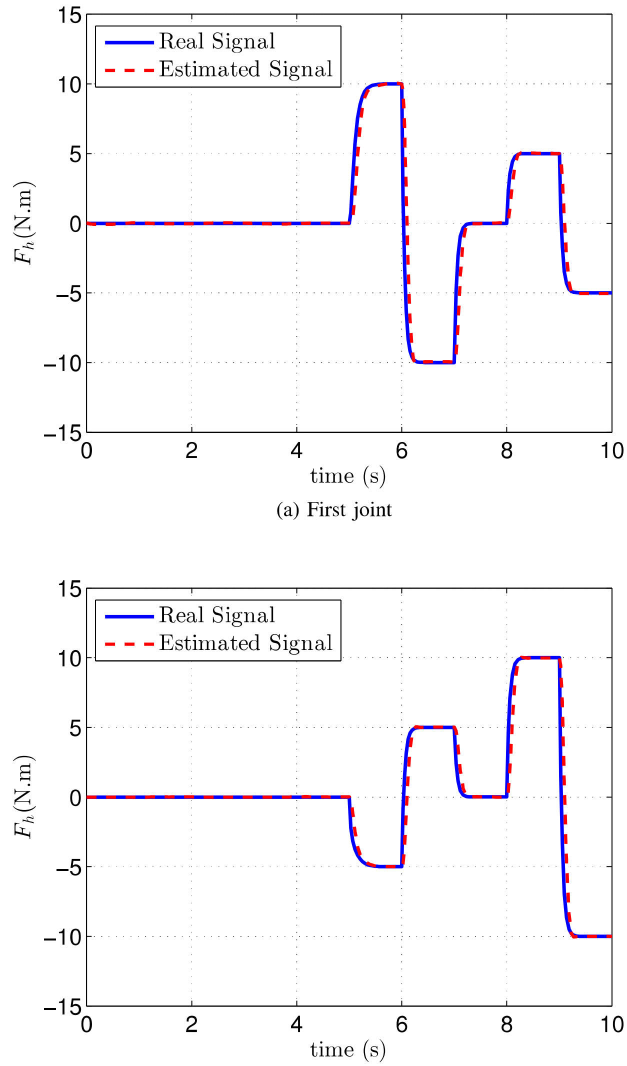


Fig. 2: The force of the trainee.



(a) First joint

(b) Second joint

Fig. 3: The real and estimated force of the trainer hand

#2. The reason is that the controller of the haptic console #1 is a position tracker controller ,whereas the controller of the haptic console #2 is just a stabilizing controller without any tracking requirement. Besides, the observer parameters are set as $a_1 = 0.07$, $a_2 = 0.0025$, and $\epsilon = 0.002$. Furthermore, the environmental forces in the task space are assumed to be defined by the following equations

$$F_{exi} = \times \begin{cases} -K_e x_i, & x_i \leq 0 \\ 0, & x_i > 0 \end{cases} \tag{37}$$

where K_e is the stiffness of the environment and it is assumed that $K_e = 10$. The environmental forces in the joint space are computed as

$$F_e = J_2^T(q) \times \begin{bmatrix} F_{ex1} \\ F_{ex2} \end{bmatrix} \tag{38}$$

where $J_2(q)$ is the Jacobian of the robot. The forces applied by the trainee are assumed to be repeating sequence stair signals passed from the filter $\frac{1}{0.05s+1}$. The corresponding plots are depicted in Fig. 2. The real and estimated force signals applied by the trainer are depicted in Fig. 3. The real and estimated signals are shown by blue (solid) and red (dashed) lines, respectively. The real force of the trainer is assumed to be zero from $t = 0s$ to $t = 5s$, and filtered repeating sequence stair signals from $t = 5s$ to $t = 10s$. As displayed in the figure, the estimated force signals follow the real ones appropriately. The trajectories of the haptic consoles in the joint space are presented in Fig. 4. The position signals of the trainee and the trainer are shown by blue (solid) and red (dashed) lines, respectively. This figure show the appropriate tracking performance of the control structure. The environmental forces are shown in Fig. 5. It is easy to see that the contact with the environment does not damage the stability of the system.

V. Conclusions

In this paper, a robust force reflection control scheme with a high gain observer is developed for the dual user haptic surgical training system. The stability of the closed-loop system is investigated using the ISS stability theorem. The simulation results demonstrates the effectiveness of the proposed control scheme. The stability analysis of the proposed control scheme is just proved in the presence of dynamic uncertainties. In the robotic systems, there are other kinds of uncertainties such as kinematic and unstructured uncertainties which are not considered in this investigation. The stability analysis of the haptic surgical training system in the presence of these kinds of uncertainties is currently being examined in our research. Furthermore, implementation of the proposed controller in our experimental setup will be followed in the next step.

Acknowledgments

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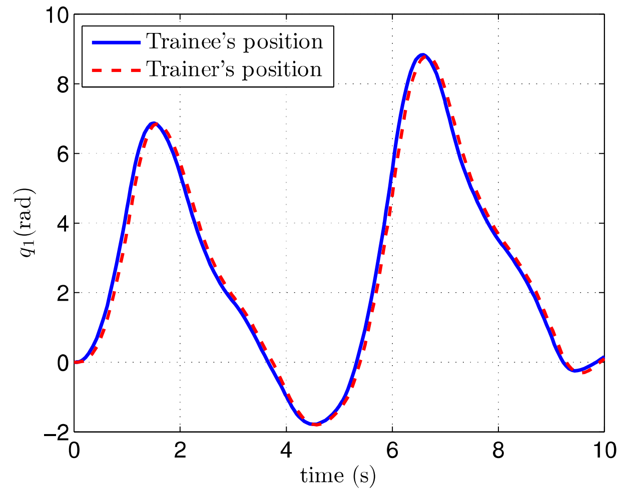
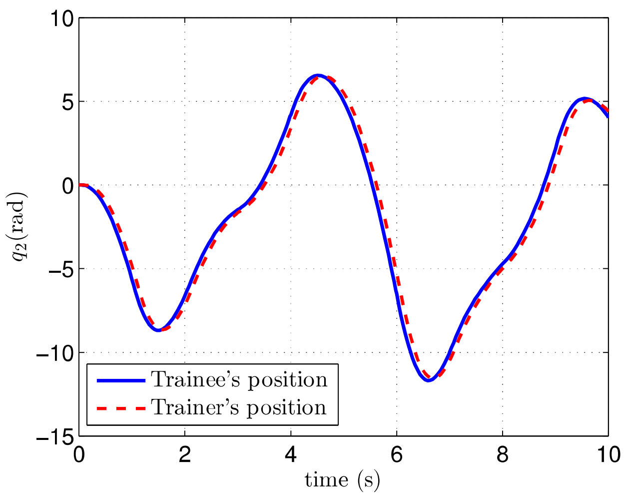


(a) First joint



(b) Second joint

Fig. 4: Trajectories of the first and second joint of the haptic consoles

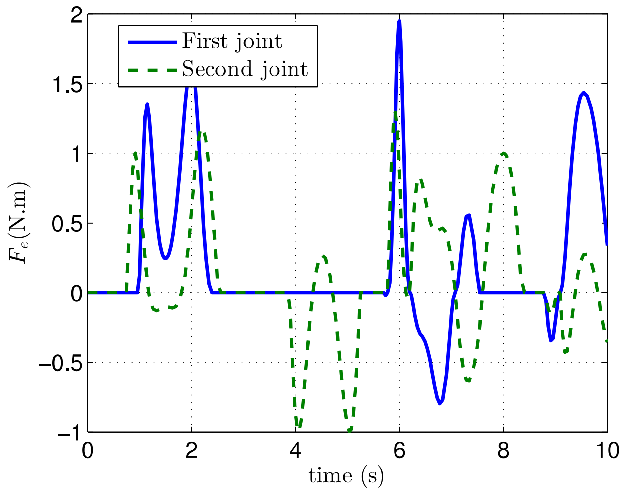


Fig. 5: Environmental forces.

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