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Robust Impedance Control for Dual User Haptic Training System

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***Abstract*—In this paper, an impedance controller with switching parameters for a dual-user haptic training system is introduced. The trainer and the trainee are connected through their haptic consoles, and the trainee performs the surgical procedure on the environment. The trainer can intervene in the procedure by pressing a mechanical pedal; thus, the control parameters are switched to transfer the authority over the task from the trainee to the trainer. The stability of each subsystem and the closed-loop stability of the overall system are investigated. The simulation results verify the performance of the proposed controller.**

***Index Terms*—Teleoperation, Dual-user, MIS, Surgery training, Impedance control, Dwell time**

I. Introduction

Teleoperation methods have been used in many applications, particularly in high-risk tasks, from bomb disposal and space exploration to surgery. The human operators performing these operations usually benefit from visual and tactile feedback to better understand what they are interacting with. In surgical applications of teleoperation, surgeons need to insert instruments through a small incision in the patient's body, which is called Minimally Invasive Surgery (MIS). In this type of surgery, the provision of visual and tactile signals is challenging. Even though by providing 2D images to the surgeon, his/her understanding of depth is impaired. Moreover, owing to the long length of the surgical instrument, the surgeon's force alignment is not the same as the tool. Constrained operative workspaces, on the other hand, limit the robot's performance. [1], [2].

Haptic technology is one of the most challenging areas in robotics. Providing haptics feedback is very useful in teleoperation applications owing to giving a sense of presence for a user who does not have direct access to the environment. Haptic devices can help operators feel the environment as if they are acting on it directly. Dual user haptic systems are also used to perform cooperative tasks, for instance, in robot-assisted MIS for training purposes. High-skilled surgeons (the trainers) can assist those who do not have enough experience in surgery (the trainees) to improve their skill level.

In traditional training, the trainer holds the trainee's hands to correct his/her movements. In this setup, the trainer holds his/her hands firmly if the trainee does not perform well. Therefore, the extra weight on his/her hand guide the trainee through the right path and also increase the expertness of trainee over time.

In modern surgical training, the novice can gain a better understanding of the surgical process through feedback from the expert provided by the haptic system. Furthermore, The expert can quickly take control of the process from the novice if needed and prevent the possible damage. This collaboration in training is made possible by the use of dual-user haptic systems. This system comprises of two haptic devices for both users and a slave robot to perform a task on an environment.

The control objective for the dual user training system is to imitate the traditional training scenario. The trainee can take control of his/her haptic device, which is directly in contact with the virtual or real environment after obtaining some level of expertise in surgery and performs the surgery. In fact, by removing the slave robot from the conventional structure of dual user systems, the trainee interacts directly with the environment. The trainer monitors the operation through another haptic device that is synchronous with the trainee's haptic device. Feedback from positions and forces are passed to the trainee's side to offer the appropriate haptic clues and guide along the right operation trajectory.

This guidance is provided through the proposed impedance controller located on the trainee's side. The controller appropriately adjusts the relationship between force and position feedback according to the desired impedance equation, which is set in the controller [3]. The appropriate control law is applied to the trainee's haptic device to correct his/her maneuvers. In the past decade, many control strategies have been proposed in the literature such as robust Control [4], adaptive force reflecting control [5], six-channel control architecture [6], virtual fixture based control [7], S-shaped function-based control architecture [8] and adaptive control [9]. Moreover, a systematic review of multilateral haptic systems is presented in [10]. The work presented in this paper builds upon the idea of [11] and [12] by implementing the robust impedance control, which guarantees zero impedance error between the two devices in dual user systems.

The proposed control scheme consists of two operating modes. In the first mode, when the trainee is doing the surgery without any considerable error, loose impedance control is applied to his/her haptic device. The term 'loose' is referred to as low-valued inertia, damping, and stiffness parameters in the impedance controller. Once the trainee performs a wrong maneuver, the trainer will push the pedal to correct him/her. At this moment, the control system is switched to

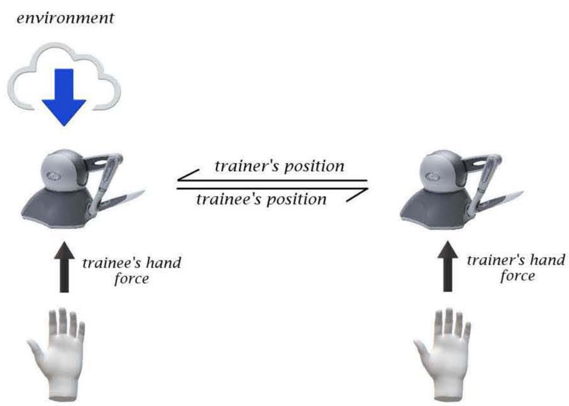


Fig. 1: The proposed haptic framework for surgery training.

the second mode, which is called a tight impedance control. The impedance control stays in this mode until the trainer presses the pedal another time to dominate the trainee again.

The rest of the paper is organized as follows. In section II, the system description and the robust Impedance control law is presented. The stability analysis based on the Lyapunov theory and dwell time stability for switching systems is presented in Section III. Section IV presents simulation results. Finally, the concluding remarks are stated in section V.

II. Control Strategy

Consider the block diagram of the proposed control scheme for a dual-user haptic training system depicted in Fig. 1. The trainee's haptic device is in contact with the environment; thus, the interaction force is applied to his/her device. The general n-DoF dynamical model of the trainer and the trainee's haptic devices in the joint space are given by

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = \tau_i + J_i^T f_{ext_i}, \quad (1)$$

where the matrix $M_i(q_i)$ denotes the $n \times n$ positive definite inertia matrix of the system, $C_i(q_i,\dot{q}_i)\dot{q}_i$ represents the $n \times 1$ centripetal and Coriolis terms, $G_i(q_i)$ is the $n \times 1$ gravity vector and τ_i is the torque control effort. The vector f_{ext_i} represents the external forces applied by the operators and environment which is f_{h_1} for $i = 1$ and $f_{h_2} - f_e$ for $i = 2$.

The kinematic transformations between the joint and Cartesian spaces are expressed as

$$\begin{aligned} x_i &= f_i(q_i) \\ \dot{x}_i &= J_i(q_i)\dot{q}_i \\ \ddot{x}_i &= \dot{J}_i(q_i)\dot{q}_i + J_i(q_i)\ddot{q}_i, \end{aligned}$$

where $x_i \in \mathbb{R}^{n\times 1}$ is the position vector in task space coordinates and $q_i \in \mathbb{R}^{n\times 1}$ is the vector of joint angles of the manipulators. The subscript i denotes the trainer's console for $i = 1$ and trainee's console for $i = 2$. The function $f_i(.)$ is found from the robot forward kinematics. The matrix $J_i \in \mathbb{R}^{n\times n}$ is the jacobian of each device which is defined as $J_i(q) = \partial f_i(q_i)/\partial(q_i)$.

The dynamic formulation is written in Cartesian space as follows so that impedance controllers can be applied to the system.

$$M_{x_i}(x_i)\ddot{x}_i + C_{x_i}(x_i,\dot{x}_i)\dot{x}_i + G_{x_i}(x_i) = J_i^{-T}\tau_i + f_{ext_i}, \quad (2)$$

where

$$\begin{aligned} M_{x_i}(x_i) &= J_i^{-T} M_i(q_i) J_i^{-1} \\ C_{x_i}(x_i,\dot{x}_i) &= J_i^{-T}(C_i(q_i,\dot{q}_i) - M_i(q_i))J_i^{-1}\dot{J}_i)J_i^{-1} \\ G_{x_i}(x_i) &= J_i^{-T} G_i(q_i). \end{aligned}$$

The equation (2) has some useful properties that are listed as follows [13]:

Property 1. The inertia matrix $M_x(x)$ is symmetric, uniformly positive definite and bounded for all $x \in \mathbb{R}^n$ by

$$\underline{m} I_{n\times n} \le M_x(x) \le \overline{m} I_{n\times n}. \quad (3)$$

Property 2. Upper bound of $C_x(x,\dot{x})$ is independent of x, and is a function of $\dot{x}$ as

$$\| C_x(x,\dot{x}) \| \le \gamma_c \| \dot{x} \| . \quad (4)$$

Property 3. Gravity term is upper bounded as

$$\| G_x(x) \| \le \gamma_g. \quad (5)$$

Property 4. The matrix $\dot{M}_x(x) - 2C_x(x,\dot{x})$ is skew symmetric and therefore, for all $\xi \in \mathbb{R}^n$

$$\xi^T \left(\dot{M}_x(x) - 2C_x(x,\dot{x})\right) \xi = 0. \quad (6)$$

Afterward, the proposed control algorithm for a dual-user surgical haptic training system is explained. The control system suggested in this paper applies to both the trainee's and the trainer's haptic devices. The controller produces a desired dynamic behavior between the human operator and the haptic console, which is robust to the parametric uncertainties and hard nonlinearities. The desired impedance in the time domain is

$$M_{d_i}(\ddot{x}_{d_i} - \ddot{x}_i) + B_{d_i}(\dot{x}_{d_i} - \dot{x}_i) + K_{d_i}(x_{d_i} - x_i) = f_{m_i}, \quad (7)$$

where f_{m_i} is the measured force from haptic devices which is $f_{h_i} - f_{env}$. The matrices M_d, B_d, and K_d are desired inertia, damping, and stiffness of the impedance model. For each haptic console, x_{d_i} is defined as the position of the other haptic console. Therefore, the impedance error is defined as

$$I_i(t) = M_{d_i}\ddot{e}_i + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{m_i}, \quad (8)$$

where e_i denotes the position error. Now, a sliding surface is defined as

$$s_i = \int_0^t M_{d_i}^{-1} I_i(\tau) d\tau = 0. \quad (9)$$

Sliding mode structure based on impedance control is applied for tracking the trainer's position by the trainee's haptic device as well as achieving zero impedance error in the presence of uncertainty in dynamics. In this case, the closed-loop dynamics is in the form of Eq. (7).

When the trainee is doing the surgery, and the trainer approves his/her movements with reasonable error, the following control torque is applied on his/her console

$$\tau_i = J_i^T(\hat{M}_{x_i} a_{x_i} + \hat{C}_{x_i}\dot{x}_i + \hat{G}_{x_i} - f_{ext_i}), \tag{10}$$

where

$$a_{x_i} = M_{d_i}^{-1}(M_{d_i}\ddot{x}_d + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{ext_i} + M_{d_i}K_{g_i}\text{sgn}(s_i)). \tag{11}$$

The $\hat{(.)}$ denotes the available estimation of dynamic terms, $K_{g_i} = k_{g_i}I_{n\times n}$ is a symmetric diagonal positive definite matrix and signum function is defined as follows:

$$\text{sgn}(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \tag{12}$$

Equation (10) is sorted and classified by addition and subtraction of the term $J_i^T M_{x_i} a_{x_i}$ from the control law (10), then by substituting the control law in the dynamic equation (2), the closed loop dynamic equation is obtained as

$$\ddot{x}_i = a_{x_i} + M_{x_i}^{-1}(\tilde{M}_{x_i}a_{x_i} + \tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i}), \tag{13}$$

in which,

$$\tilde{M}_{x_i} = M_{x_i} - \hat{M}_{x_i},\ \tilde{C}_{x_i} = C_{x_i} - \hat{C}_{x_i},\ \tilde{G}_{x_i} = G_{x_i} - \hat{G}_{x_i}.$$

Note that

$$M^{-1}\tilde{M} = M^{-1}\hat{M} - I =: E. \tag{14}$$

From (14) and (13), the closed loop dynamics is obtained as

$$\ddot{x}_i = a_{x_i} + Ea_{x_i} + M_{x_i}^{-1}(\tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i}), \tag{15}$$

in which the dynamic uncertainty is defined as

$$\eta_i = Ea_{x_i} + M_{x_i}^{-1}(\tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i}). \tag{16}$$

According to the properties of the robot dynamics model, which are denoted in the previous section, it is concluded that

$$\|\eta_i\| = \|Ea_{x_i} + M_{x_i}^{-1}(\tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i})\| \leq \rho_i(s,t), \tag{17}$$

in which $\rho_i(s,t)$ is a time-varying scalar bound on the uncertainty.

For both haptic consoles, M_{d_i}, B_{d_i}, and K_{d_i} are fixed during the operation, but their values are switched according to the state of the pedal. When the pedal is not pressed, the impedance parameter values are chosen in such a way that the novice surgeon dominates the operation. Furthermore, whether the trainer intends to have more control over the task, the impedance parameters on the trainer's side are reduced to enhance the maneuverability of the haptic device.

III. Stability Analysis

The Lyapunov theory [14] is used to study the closed-loop stability of the trainer's and the trainee's haptic devices in *Proposition 1* and *Proposition 2*, respectively. *Proposition 3* deals with the stability of the switching system using average dwell time theory [15]. The overall system stability is discussed in *Theorem 1*.

Proposition 1: The trainee's haptic console subsystem is stable in the sense of Lyapunov and will converge to the desired impedance (7).

Proof: Consider the following Lyapunov function candidate for trainee's console as

$$V = s_i^2/2 \tag{18}$$

in which, s_i is defined in Eq. (9). By differentiating V with respect to time and using Eqs. (8) and (9), we have

$$\dot{V} = s_i M_{d_i}^{-1}(M_{d_i}(\ddot{x}_d - \ddot{x}_i) + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{ext_i})$$

By substituting $\ddot{x}_i$ with Eq. (15), it adds to

$$\dot{V} = s_i M_{d_i}^{-1}(M_{d_i}\ddot{x}_d - M_{d_i}(a_{x_i} + \eta_i) + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{ext_i})$$

If the Eq. (11) is included within the $\dot{V}$, the result is

$$\begin{aligned}\dot{V} &= s_i M_{d_i}^{-1}(M_{d_i}\ddot{x}_d - M_{d_i}(M_{d_i}^{-1}(M_{d_i}\ddot{x}_d + B_{d_i}\dot{e}_i + K_{d_i}e_i \\ &- f_{ext_i} + M_{d_i}K_{g_i}\text{sgn}(s_i)) + \eta_i) + B_{d_i}\dot{e}_i + K_{d_i}e_i \\ &- f_{ext_i}) = s_i M_{d_i}^{-1}(-M_{d_i}K_{g_i}\text{sgn}(s_i) - \eta_i) \\ &= -K_{g_i}|s_i| - s_i M_{d_i}^{-1}\eta_i \leq -K_{g_i}|s_i| - M_{d_i}^{-1}\rho_i s_i\end{aligned}$$

so, if $K_{g_i} > |M_{d_i}^{-1}\rho_i|$, then it proves the convergence of the dynamics of the trainee's device to the desired impedance. □

Proposition 2: The trainer's haptic device subsystem is stable, and the stability analysis is the same as the trainee's haptic device regarding the identical control structure. □

Proposition 3: There is a finite constant τ_D^* such that both the trainee's and the trainee's closed-loop dynamics is uniformly asymptotically stable over switching signal, for any average dwell-time $\tau_D \geq \tau_D^*$ [16].

Proof: In order to prove the dwell time stability of both haptic device, a Lyapunov function with the following property should be chosen

$$V_l \leq \mu V_t, \tag{19}$$

where subscripts 'l' and 't' are referred to as 'loose,' and 'tight' in impedance gains and μ is a positive constant. Consider the same Lyapunov function candidate for trainee's console (18). It yields

$$\frac{M_{d_l}^2 V_l}{M_{d_t}^2 V_t} = \frac{\frac{1}{2}[\int_0^t (M_{d_l}\ddot{e}_l + B_{d_l}\dot{e}_l + K_{d_l}e_l - f_{m_l})d\tau]^2}{\frac{1}{2}[\int_0^t (M_{d_t}\ddot{e}_t + B_{d_t}\dot{e}_t + K_{d_t}e_t - f_{m_t})d\tau]^2}. \tag{20}$$

If the measured force f_m has an upper bound $\overline{f}$ and lower bound $\underline{f}$, by defining

$$\begin{aligned}
\alpha &= \frac{M_{d_l}^2}{M_{d_t}^2} \\
p_l &= [M_{d_l}, B_{d_l}, K_{d_l}] \\
p_t &= [M_{d_t}, B_{d_t}, K_{d_t}] \\
x_l &= [\int_0^t \ddot{e}_l(\tau)d\tau, \int_0^t \dot{e}_l(\tau)d\tau, \int_0^t e_l(\tau)d\tau]^T \\
x_t &= [\int_0^t \ddot{e}_t(\tau)d\tau, \int_0^t \dot{e}_t(\tau)d\tau, \int_0^t e_t(\tau)d\tau]^T,
\end{aligned} \tag{21}$$

then the Eq. (20) can be written as

$$\frac{V_l}{V_t} \leq \frac{1}{\alpha}(\frac{p_l x_l - \overline{f}}{p_t x_t - \underline{f}})^2. \tag{22}$$

Equation (22) can be expressed in the form of Eq. (19) using the maximum value for $\frac{V_l}{V_t}$, which is

$$max(\frac{V_l}{V_t}) = \frac{1}{\alpha}(\frac{p_l \dot{x}_l}{p_t \dot{x}_t})^2. \tag{23}$$

This maximum value can be written in the following form using Eqs. (21)

$$\frac{V_l}{V_t} \leq \frac{1}{\alpha}(\frac{f_{m_l}}{f_{m_t}})^2 \leq \mu. \tag{24}$$

And μ is the upper bound of $\frac{1}{\alpha}(\frac{f_{m_l}}{f_{m_t}})^2$. □

Theorem 1: The interconnected system with the dynamic equation (2) and the control law (10) is stable.

Proof: The sum of the energy of two subsystems becomes the sum of the energy of two Lyapunov functions, and because each Lyapunov function has bounded energy, therefore, the overall system is stable. □

IV. Simulation Results

The control scheme proposed in this paper is applied to two similar Geomagic Touch^{TM} devices. The dynamics of these devices are given in [17]. The main parameters in the haptic dynamic model, such as mass and length of the links have been perturbed by 20% of their original value in order to properly evaluate the robustness of the system. The simulations are obtained using the ode15s solver in Matlab Simulink by setting a fixed step size equals to $1e-5$. The simulation results are given for the third DoF of haptic devices for the sake of simplicity of the representation. This selection is because of the importance of this DoF rather than other degrees of freedom in surgery, but the results are the same for other DoFs. Moreover, the contact force of the environment is based on the Hunt–Crossley contact model, which is introduced in [18]. This model can be used as an alternative to soft tissue dynamic model [19]. The contact force is defined as:

$$f_{env} = \begin{cases} K_e x^n(t) + B_e \dot{x}(t) x^n(t) & x > 0 \\ 0 & x \leq 0 \end{cases} \tag{25}$$

in which $Ke = 10$, $Be = 2$ and $n = 1.2$ are selected in this simulation. This force is illustrated in Fig. 2b.

The expert force generation method is as follows: First, a sinusoidal signal with the required amplitude is applied to the inverse dynamics model. The generated torque is then exerted to the forward dynamics; thus, the desired trajectory is obtained in the joint space. This trajectory is tracked with a PD control, leading to a motion in a task space similar to the original sinusoidal path. Since this sinusoidal hand force causes a meaningful and conventional maneuver in task space, e.g., sweeping a space by reciprocating movements, this choice for the hand force signal would be appropriate.

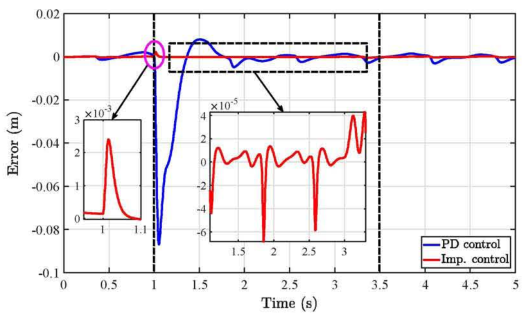
Now we want to show somehow that the novice surgeon has made a sudden mistake, for example, his/her hand has been twitched abruptly. By this mean, a pulse with an amplitude of $1\ N$ for $0.05\ s$ is applied to the trainer's hand force at $T = 1\ s$. Then the resulting signal is considered as a trainee's hand force. This pulse indicates an abrupt error by the novice. If PD controllers control both the novice and expert's sides, the error takes about $2\ s$ to eliminated, and the value of the position tracking error between two consoles is large. In Fig. 2a, the blue line shows the tracking error due to this pulse.

The red line in Fig. 2a is the result of applying the proposed controller to the novice's haptic device. The same pulse is inserted at $T = 1\ s$, but in $[1 - 3.5]$ time interval pedal is pushed by the expert to prevent damages to the patient. Therefore, the desired impedance parameters switch from $M_{d_l} = 0.001 I_{3\times3}$, $B_{d_l} = 4 I_{3\times3}$ and $K_{d_l} = 100 I_{3\times3}$ to $M_{d_t} = 0.0001 I_{3\times3}$, $B_{d_t} = 20 I_{3\times3}$ and $K_{d_t} = 1000 I_{3\times3}$ at $t = 1\ s$. Subscripts 'l' and 't' are referred to 'loose' and 'tight' modes. It can be seen that switching impedance gains, greatly reduces the error both inside and outside the switching window.

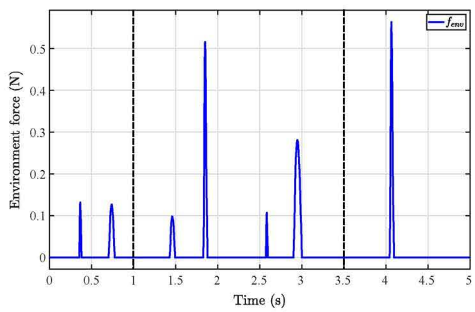
The performance of the controller during abrupt errors was evaluated, and its superiority over the PD controller was shown. The performance of the controller is monitored when dealing with the environment. In addition to the pulse that was previously added, the environment forces generated by the Hunt–Crossley model is applied to the trainee's haptic device. Moreover, the trainer's hand force perturbed by 15% is considered as the trainee's hand force.

In Fig. 2c, two sides of desired impedance equation (7) are plotted. As it is shown, both plots are not always the same, but they follow each other with a little difference. This proves that the goal of impedance control and verifies how well the relationship of force and motion with the required impedance dynamics has been adjusted. The impedance gains are altered to greater values at $T = 1\ s$. Thus, the distinction between the two plots is minimal within the time interval shown by the black dashed line.

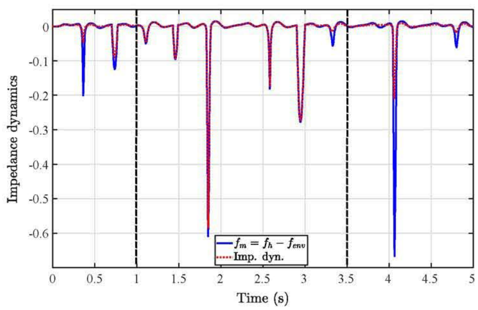
Changing the desired impedance coefficients also results in a significant reduction in tracking error. In $[1 - 3.5]$ period, when the expert detects that the error has been exceeded by the novice from its safe area, control becomes tighter and dramatically reduces the error amplitude. Positions of the trainee and the trainer during the surgical procedure are shown in Fig. 2d. What can be seen in this figure is the rapid decrease in the amount of tracking error in $[1-3.5]$ s. Outside of this period, the trainee is the dominance user; hence, he/she can freely maneuver within the robot's workspace. However, in the $[1-3.5]$ with the intervention of the trainer in operation, the trainee is forced to follow in his/her movements.



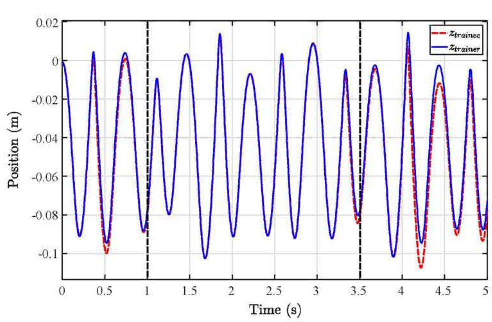
(a) Positions error



(b) Environment force



(c) Impedance dynamics



(d) Positions of the trainer and the trainee

Fig. 2: Simulation results.

V. Conclusion

In this paper, a switching gain impedance control is introduced for the dual user haptic training system. The stability of the system is studied using the Lyapunov stability approach and dwell time theory. Through simulation results, it is shown that the proposed control scheme is entirely practical for the dual user training system. Further research should be carried out to decrease the stability conditions and explore how the proposed control algorithm is effective in implementation.

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