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Novel Shared Control Architectures for Enhanced Users' Interaction in Haptic Training Simulation Systems

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***Abstract*— This paper proposes two new multilateral shared control architectures for dual-user haptic training systems. Similar to the architecture previously proposed in [1], the controllers allow interaction between both users, the trainee and the trainer, as well as between the users and the virtual slave robot and environment. However, the newly proposed architectures provide increased maneuverability and enhanced sense of environment to the users. The kinesthetic performance of the proposed control architectures are analyzed under different operating conditions. Furthermore, the architectures are implemented on a dual-user haptic simulation testbed for user study experiments to investigate the effectiveness of the proposed architectures in terms of sense of environment, maneuverability, and guidance.**

I. Introduction

In dual-user haptic simulation systems two users perform a task collaboratively in a shared virtual environment. Emerging applications of such systems have been in human haptic guidance for skill training and rehabilitation [2], [3], [4]. There has been a number of architectures proposed for the control of dual-user haptic systems [2], [3], [4], [5], [6].

In the cooperative architecture presented in [4], both master robots interact independently with a virtual object, which is considered as the slave. However, there is no connection between the two masters. In [5] a dual-user haptic training system with a four-channel multilateral controller has been developed. The control architecture consists of a position controller responsible for maintaining position correspondence between the three robots, and a force controller to assure the net zero sum of the forces in the system. A two-channel multilateral force-position architecture with adaptive nonlinear controller has also been proposed in [6] to achieve desired position/force mappings for collaborative haptic training. However, the above control architectures do not report any user dominance over the task.

An H∞-based shared control architecture for haptic collaboration between a trainer and a trainee in performing telesurgery has been proposed in [3]. The control authority shared between the surgeons is chosen based on their relative level of surgical skills. In this architecture, the slave robot is controlled unilaterally and no kinesthetic feedback is provided to the users from the slave. The design of the above architectures do not consider the operators maneuverability and perception from the environment. Furthermore, they did not report any user study to evaluate the developed architectures.

Khademian *et al.* have designed a dual-user teleoperation control architecture for training purposes, so that one user (trainer) can affect the other user's (trainee's) movement through their haptic devices [1]. The users can also have no, partial or full control over the slave robot. These features are realized by introducing a dominance factor which determines the supremacy of the users over the slave robot and over each other. However, the authors noticed that when a user had low or no authority over the task, s/he would suffer from immobility and lack of the feel of the environment. As a remedy in this paper, two new architectures are proposed for higher maneuverability and enhanced sense of environment. The first proposed architecture is a four-channel multilateral shared control architecture, which guarantees a bilateral connection between the three entities *i.e.* the two masters and slave, regardless of the authority of users over the task. The second proposed architecture features a three-channel shared control architecture between the two masters and the slave robot, and bilateral position-based control architecture between the two masters.

We will also analyze the kinesthetic performance of these two new architectures by means of evaluating the transmitted impedance to the operators under different operating conditions such as various types of environments, users' grasps, and levels of dominance of users over the task. Additionally, the proposed architectures will be implemented on a dual-user haptic simulation system and a user study will be carried out to investigate the effectiveness of the proposed architectures.

II. Multilateral Shared Control Architecture

A dual-user teleoperation system consists of two master robots for two operators and one slave robot to perform a task on an environment. To analyze the above dual-user teleoperation system, the operators and environment dynamics are modeled around their operating points by the Linear-Time-Invariant (LTI) one-port networks, $F_{hi} = F^*_{hi} - Z_{hi}V_{hi}$ and $F_e = F^*_e + Z_eV_e$, where Z_{hi}, $i = 1, 2$, and Z_e are the operators' arm and environment impedances, V_{hi}, $i = 1, 2$ and V_e denote operators and environment positions, F_{hi}, $i = 1, 2$, and F_e denote the operators' forces applied to the master robots and the slave force exerted on the environment, and F^*_{hi}, $i = 1, 2$ and F^*_e denote the exogenous force inputs generated by the operators and the environment, respectively. Assuming that the operators are interfaced with the master devices and the slave is in contact with the environment,

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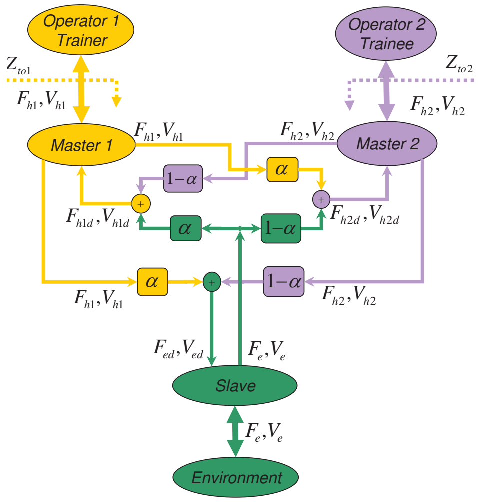


Fig. 1. Block diagram of the existing four-channel control architecture.

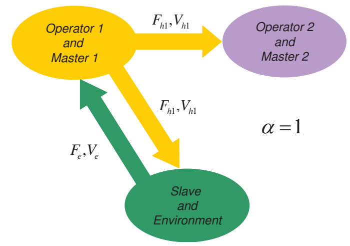


Fig. 2. Training mode ($\alpha = 1$) in the existing architecture: the master 1 and the slave form a four-channel bilateral architecture.

the masters and the slave linear dynamics are modeled in Laplace domain as: $Z_{mi}V_{hi} = F_{hi} + F_{cmi}$ and $Z_s V_e = -F_e + F_{cs}$, where $Z_{mi} := M_{mi}s$, $i = 1, 2$ and $Z_s := M_s s$ represent LTI mass models of force actuated master and slave manipulators. The control commands:

$$F_{cm_i} = -C_{m_i}V_{hi} - C_{4m_i}V_{hid} + C_{6m_i}F_{hi} - C_{2m_i}F_{hid} \quad (1)$$

$$F_{cs} = -C_s V_e + C_1 V_{ed} - C_5 F_e + C_3 F_{ed} \quad (2)$$

realize a four-channel architecture [7], [8], where $C_{m_i} := B_{m_i} + \frac{K_{m_i}}{s}$, $i = 1, 2$, and $C_s := B_s + \frac{K_s}{s}$ denote local PD position controllers, C_{6m_i}, and C_5 are local force controllers, C_1, C_{2m_i}, C_3, and C_{4m_i} are remote compensators, V_{hid} and V_{ed} are the desired positions, and F_{hid} and F_{ed} are the desired forces for masters and slave robots transmitted through the communication channel.
To provide perfect transparency under ideal condition of no time delay, the *transparency-optimized* control parameters in (1)-(2) are selected as: $C_1 := Z_s + C_s := Z_{cs}$, $C_{2m_i} := 1 + C_{6m_i}$, $C_3 := 1 + C_5$, and $C_{4m_i} := -(Z_{m_i} + C_{m_i}) := -Z_{cm_i}$, and $(C_{2m_i}, C_3) \neq (0,0)$ for $i = 1, 2$ [1]. In the controller, $Z_{cm_i} := Z_{m_i} + C_{m_i}$, $i = 1, 2$, and $Z_{cs} := Z_s + C_s$ are the closed-loop dynamics of the position controlled masters and slave. This controller guarantees that position and force signals reach their desired values, *i.e.* $V_{hi} \to V_{hid}$, $V_e \to V_{ed}$, $F_{hi} \to F_{hid}$, $F_e \to F_{ed}$. The choice of V_{hid}, V_{ed}, F_{hid}, and F_{ed} results in different control architectures. Next, the existing four-channel architecture is presented and the two newly proposed architectures is introduced.

A. Existing Architecture

The four-channel multilateral shared control architecture introduced in [1] is shown in Figure 1. The desired position and force commands for each robot are a weighted sum of positions and forces of the other two robots, which for desired positions are:

$$V_{h1d} = \alpha V_e + (1-\alpha)V_{h2} \quad (3)$$

$$V_{h2d} = (1-\alpha)V_e + \alpha V_{h1} \quad (4)$$

$$V_{ed} = \alpha V_{h1} + (1-\alpha)V_{h2} \quad (5)$$

and the same relations are in place for F_{h1d}, F_{h2d}, and F_{ed}. The weights are specified by a *dominance factor*, α, which determines the supremacy of each user over the slave and varies between zero and unity. The control authority of operator 1 and operator 2 over the slave robot are determined by α and $1-\alpha$, respectively.
The above control architecture is designed for training purposes. When $\alpha = 1$, master 1 and the slave form a four-channel bilateral teleoperation system (Figure 2). In this training mode, the motion of master 2 is fully controlled by master 1, and thus operator 2 (trainee) is dragged by operator 1 (trainer). If α is between zero and unity, both operators can control the slave robot and the trainer can *guide* the trainee to perform a task collaboratively in a shared environment. A value for α can be allocated to the trainee based on the trainee's skill on performing a specific task.

However, there are two shortcoming with this architecture. When $\alpha = 1$, master 2 is cut out of the control loop (Figure 2). In this case, there is no force feedback from the environment to operator 2, leaving operator 2 with no feel of the environment. Furthermore, due to the unilateral nature of the signals flow, operator 2 cannot affect the motion of master 1 and operator 1, and thus the command from operator 1 to master 2 acts as an exogenous set-point. This set-point creates a resistance to the input generated by operator 2 and as a result low maneuverability of operator 2.

As a remedy to this problem, we propose two new architectures which guarantee maneuverability of the operators and a good perception of the environment when the operators have various level of authority over the task.

B. Proposed Architecture I

The objective is to develop a four-channel multilateral shared control architecture in which all the four channels between all three ports remain open regardless of the value of α. Therefore, the position and force contribution from each robot in the desired position and force for another robot will no longer change from full to null as α changes from 1 to 0 in (3)-(5), but changes from $\frac{n-1}{n}$ to $\frac{1}{n}$ where $n > 1$ is chosen

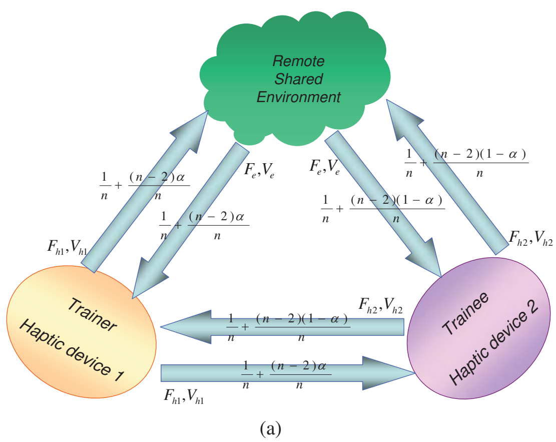


Fig. 3. Desired position and force in architecture I.

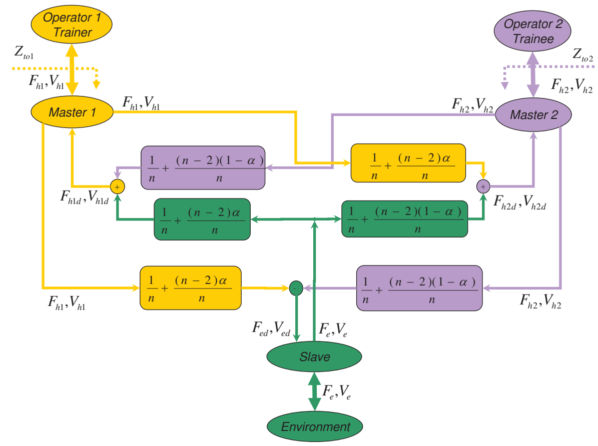


Fig. 4. Block diagram of the proposed control architecture I.

arbitrarily. The constant parameter n ($n > 1$) guarantees a four-channel bilateral connection between all three robots regardless of the value of α. Therefore, an operator will never be cut out of the control loop when α is zero or unity. This will assure that a master device with lower authority sends a minimum command/feedback to the master with higher authority which results in increased maneuverability of its operator. In addition, this provision guarantees interaction between the operator with low authority and environment which helps the operator feel the environment. Figure 3 shows the desired position and force signals needed to implement the proposed architecture, which can be formulated for desired positions as :

$$\begin{aligned}
V_{h1d} &= (\frac{1}{n} + \frac{(n-2)\alpha}{n})V_e + (\frac{1}{n} + \frac{(n-2)(1-\alpha)}{n})V_{h2} \\
V_{h2d} &= (\frac{1}{n} + \frac{(n-2)(1-\alpha)}{n})V_e + (\frac{1}{n} + \frac{(n-2)\alpha}{n})V_{h1} \\
V_{ed} &= (\frac{1}{n} + \frac{(n-2)\alpha}{n})V_{h1} + (\frac{1}{n} + \frac{(n-2)(1-\alpha)}{n})V_{h2}
\end{aligned}$$

and for desired forces, F_{h1d}, F_{h2d}, and F_{ed}, the same relations are in place.

The block diagram of this shared control architecture is shown in Figure 4. Note that there is multilateral communication between all three robots for all values of α. If $n = 1$, this architecture turns into the old architecture explained in Section II-A with the role of the two operators reversed. If $n = 2$, the authority of each operator over the slave is 50% which cannot change with α. We are not interested in these two cases as the former is similar to the old architecture and in the latter the concept of training is neglected. The objectives of this new design is achieved for $n \geq 3$. In the case of $n = 3$, symbolically $\frac{2}{3}$ of the command signal for a robot is received equally from the other two robots ($\frac{1}{3}$ each) and the remaining $\frac{1}{3}$ is split between the two depending on the value of α. For instance when $\alpha = 1$, $V_{ed}(1) = \frac{2}{3}V_{h1} + \frac{1}{3}V_{h2}$. As the authority is transfered to operator 2 for $\alpha = 0$, $V_{ed}(0) = \frac{1}{3}V_{h1} + \frac{2}{3}V_{h2}$, the slave robot is controlled by master 1 and master 2 with portions of $\frac{1}{3}$ and $\frac{2}{3}$, respectively. If n increases this architecture becomes more similar to the old architecture mentioned in Section II-A, and for $n \to \infty$ the two become identical.

C. *Proposed Architecture II*

The idea is to grant both operators maneuverability, and a good feel of environment regardless of their authority over the task. Figure 5 shows the proposed shared control architecture which realizes our objectives.

To give both operators maneuverability and correspondence there is always a bilateral position-based connection between the two masters regardless of the value of α. Therefore, the desired position signals for each master as depicted in Figure 6 come directly from the other master, that is

$$V_{h1d} = V_{h2}, \quad V_{h2d} = V_{h1} \tag{6}$$

For users to feel the environment, there should always be some level of feedback from environment to masters through haptic devices regardless of the value of α. In this architecture, half of the environment forces is directly fed back to each master, as shown in Figure 6, that is

$$F_{h1d} = \frac{F_e}{2}, \quad F_{h2d} = \frac{F_e}{2} \tag{7}$$

The effect of the rest of the environment force is indirectly sent through the other master.

Finally the slave robot is controlled based on the users' authority over the task determined by α. Therefore, the position and force commands to the slave robot are similar to those in the old architecture in (5). In the following, the kinesthetic performance of the proposed architectures are evaluated.

III. Kinesthetic Performance Analysis

A. *Performance Measure*

Transparency is one of the major goals in the design of teleoperation control architectures. In an ideal transparent single-user teleoperation system, the impedance felt by the operator, Z_{to}, equals to the environment impedance, Z_e [8].

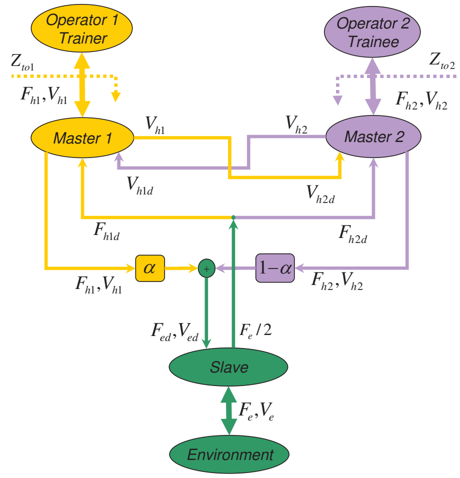
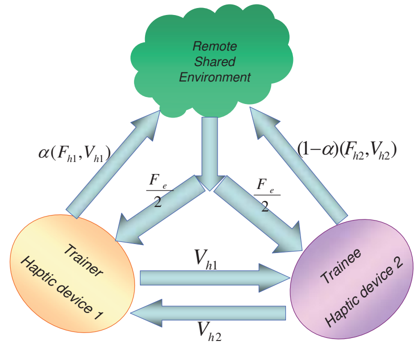


Fig. 5. Block diagram of the proposed control architecture II.



(a)

Fig. 6. Desired positions and forces of the proposed architecture II.

However, in dual-user teleoperation systems the transmitted impedance to each operator is not only affected by the environment dynamics but also the other operator dynamics as well. To investigate the performance of the proposed control architectures, we examine the effect of dominance factor, environment, and the other operator dynamics on the transmitted impedance to an operator. In the multilateral shared control architectures, shown in Figures 1, 4, and 5, the transmitted impedances to the operator 1, is defined as $Z_{to1} := \frac{F_{h1}}{V_{h1}}|_{F_e^*=0, F_{h2}^*=0}$ [1]. It is noticeable that in the old and the proposed architectures due to the system symmetry, Z_{to2} can be obtained from Z_{to1} by exchanging α, Z_{cm1}, Z_{cm2} and Z_{h2} with $(1-\alpha)$, Z_{cm2}, Z_{cm1}, and Z_{h1}. Therefore, we only focus on one transmitted impedance, that is Z_{to1}.

B. Numerical Performance Evaluation

For numerical performance evaluation, the master and the slave robots are assumed to be identical with the dynamics $Z := Z_{m1} = Z_{m2} = Z_s = Ms$ with $M = 0.313\ Kg$, reflecting the linearized dynamics of the 3DOF Planar Twin Pantographs which will be later used to experimentally evaluate the performance of the proposed architectures. The control parameters are selected as $C := C_{m_i} = C_s = K_d s + K_p$ with $K_p = 120\ N/m$ and $K_d = 2.4\ Nsec/m$. The control parameters were derived by trial and error to provide stability and desired performance in the experiments. We define $Z_c := Z + C$ as the dynamics of the PD controlled masters and slave. Two different levels of contacts have been considered for the slave robot. The first is the moderate contact in which the slave is in contact with an environment with the stiffness of 50 N/m, and damping of 5 $Nsec/m$, *i.e.* $Z_e = 5 + \frac{50}{s}$. The second is a hard contact in which the slave is in contact with an environment with stiffness of 5000 N/m, *i.e.* $Z_e = \frac{5000}{s}$.
The dynamic parameters of the operator 2 hand impedance were taken from [9] in which the impedance of human finger tip at different force levels have been measured. Therefore, we considered the following bounds for Z_{h2} in our simulations for *moderate* to *firm* grasp $2.7 \le m_{h2}\ (Kg) \le 4.7$, $2.8 \le b_{h2}\ (Nsec/m) \le 3$, and $113 \le k_{h2}\ (N/m) \le 600$ [9], and $Z_{h2} = 0$ if the device is not grabbed by operator 2.

[1]The condition $F_h^* = 0$ implies that the operator is at rest.

C. Transmitted Impedance to Operator 1

1) Existing Architecture: In the case of similar master and slave devices with similar controllers when there is no local force controller, *i.e.* $C_{6m_i} = C_5 = 0$, for $i = 1, 2$, the transmitted impedance to operator 1, Z_{to1}, in the old four-channel multilateral control architecture is expressed as:

$$Z_{to1} = \frac{\alpha Z_{h2} Z_e + (1-\alpha) Z_{h2} Z_c + Z_c Z_e}{\alpha Z_c + (1-\alpha) Z_e + Z_{h2}} \tag{8}$$

Since the two masters are similar, Z_{to1} and Z_{to2} are the same when α changes from 0 to 1 for Z_{to1} and from 1 to 0 for Z_{to2}, *i.e.* $Z_{to1}(\alpha) = Z_{to2}(1-\alpha)$. For the two extremes of α, ($\alpha = 0$ and $\alpha = 1$), Z_{to1} is simplified as follows:

$$Z_{to1}|_{\alpha=1} = Z_e, \quad Z_{to1}|_{\alpha=0} = Z_c \tag{9}$$

As it was expected, when $\alpha = 1$ there is a transparent bilateral four-channel architecture between master 1 and the slave robot, therefore, the transmitted impedance to operator 1 becomes Z_e. When $\alpha = 0$, $Z_{to1} = Z_c$ and operator 1 only sees the dynamics of master 1. Figure 7(a) shows the bode plot of Z_{to1} when the slave robot is in moderate and hard contacts, and operator 2 grasps master 2 moderately with $Z_{h2} = 2.7s + 2.8 + 113/s$. As α changes from 1 to 0, the transmitted impedance to operator 1 changes from Z_e to Z_c.

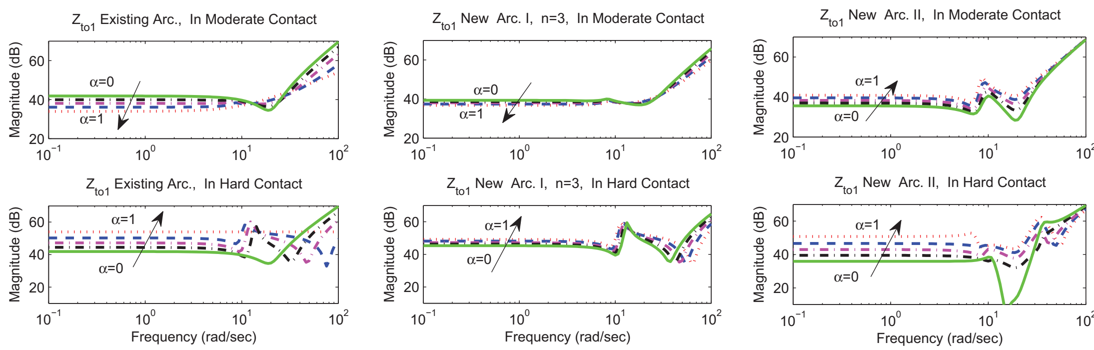
2) Proposed Architecture I: With the same condition mentioned before, the transmitted impedance to operator 1 in the first new architecture is as follows:

$$Z_{to1} = \frac{(\frac{1}{n} + \frac{(n-2)\alpha}{n}) Z_{h2} Z_e + (\frac{1}{n} + \frac{(n-2)(1-\alpha)}{n}) Z_{h2} Z_c + Z_c Z_e}{(\frac{1}{n} + \frac{(n-2)\alpha}{n}) Z_c + (\frac{1}{n} + \frac{(n-2)(1-\alpha)}{n}) Z_e + Z_{h2}} \tag{10}$$

and in the extreme cases of α it becomes:

$$Z_{to1}|_{\alpha=1} = \frac{\frac{n-1}{n} Z_{h2} Z_e + \frac{1}{n} Z_{h2} Z_c + Z_c Z_e}{\frac{n-1}{n} Z_c + \frac{1}{n} Z_e + Z_{h2}} \tag{11}$$

$$Z_{to1}|_{\alpha=0} = \frac{\frac{1}{n} Z_{h2} Z_e + \frac{n-1}{n} Z_{h2} Z_c + Z_c Z_e}{\frac{1}{n} Z_c + \frac{n-1}{n} Z_e + Z_{h2}} \tag{12}$$



(a) (b) (c)

Fig. 7. Z_{to1} in the (a) existing architecture, (b) proposed architecture I, (c) proposed architecture II, when operator 2 grasps master 2 moderately.

in which in both cases they are functions of environment, Z_e, and operator 2 dynamics, Z_{h2}.

It is noticeable that for $n = 3$ and $\alpha = 0.5$, the transmitted impedances to operator 1 in old architecture (8) and this new architecture (10) are the same. In the case of $n = 3$ and $\alpha = 1$, (11) becomes the same as $Z_{to1}|_{\alpha=0.66}$ in the old architecture. In the case of $n = 3$ and $\alpha = 0$, (12) becomes the same as $Z_{to1}|_{\alpha=0.33}$ in the old architecture. Therefore, it is expected that the range of change in the Z_{to1} plots in the proposed architecture I is less than the ones in the old architecture. Figure 7(b) shows Z_{to1} of the proposed architecture I, (10), for $n = 3$ and for different values of α when the slave robot is in contact with moderate and hard environment. The behavior of this architecture when α varies from 1 to 0, is similar to the old when α changes from 0.66 to 0.33. Therefore, as it is shown in Figure 7(b) the plots are more condense around $\alpha = 0.5$ as opposed to the old architecture in Figure 7(a).

3) Proposed Architecture II: In the case of similar master and slave devices with the transparency optimized control law mentioned in Section II, the transmitted impedance to operator 1 in the second proposed architecture can be expressed as:

$$Z_{to1} = Z_c \frac{2Z_c(Z_e + Z_{h2}) + 3\alpha Z_e Z_{h2}}{Z_e Z_{h2} + 3(1-\alpha) Z_e Z_c + 2Z_c(Z_c + Z_{h2})} \quad (13)$$

which in the extreme cases of α is still a function of operator 2 and environment dynamics.
Figure 7(c) shows the transmitted impedance to operator 1 in this new architecture for the moderate and hard contact for different α's. As α increases the magnitude of the Z_{to1} increases implying that operator 1 perceives more of the environments. The same trend is observed for moderate and hard contact. However, in hard contact the change in α value is more noticeable. This is because of the term $3\alpha Z_e Z_{h2}$ in the numerator of Z_{to1} (13) which increases and the term $3(1-\alpha) Z_e Z_c$ in the denominator which decreases as α increases. If Z_e is large, then the change in Z_{to1} magnitude would be more noticeable for two consecutive α.

D. Effect of Operator 2 Dynamics on the Transmitted Impedance to Operator 1

1) Existing Architecture: As it can be deduced from (9), in the old architecture the change in operator 2 dynamics does not have any effect on operator 1 perception when α is unity or zero. For other values of α the impedance felt by operator 1 increases as operator 2 grasps master 2 firmer. It is also shown in [1] the sensitivity of Z_{to1} to operator 2 dynamics is higher in hard environment.

2) Proposed Architecture I: Figure 8(a) shows the effect of Z_{h2} on the transmitted impedance to operator 1, (10), for $n = 3$ and for different α's in moderate and hard contact for the first new architecture. As it can be seen from the figure, for different values of α the effect of changes in Z_{h2} remains the same. These changes are very similar to those in the old architecture for α values around 0.5. From Figure 8(a) one can say that change in operator 2 dynamics has more impact on Z_{to1} in hard environment. This can be justified by examining Z_{to1}, (10), for $n = 3$ in the extreme cases of free motion and rigid environment, that is:

$$Z_{to1}|_{Z_e=0} = \left((1+\alpha)Z_c || Z_{h2}\right)\left(\tfrac{2-\alpha}{1+\alpha}\right) \quad (14)$$

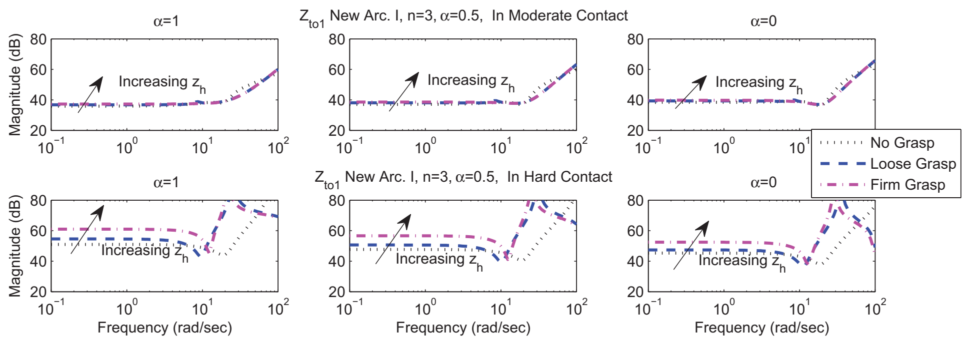
$$Z_{to1}|_{Z_e\to\infty} = \frac{Z_c + (1+\alpha)Z_{h2}}{2-\alpha} \quad (15)$$

When the slave robot is in free motion, the transmitted impedance to operator 1 is proportional to the parallel impedance of $(1+\alpha)Z_c$ and Z_{h2}. However, in hard environment, the transmitted impedance to operator 1, (15), is proportional to the series impedance of Z_c and $(1+\alpha)Z_{h2}$.

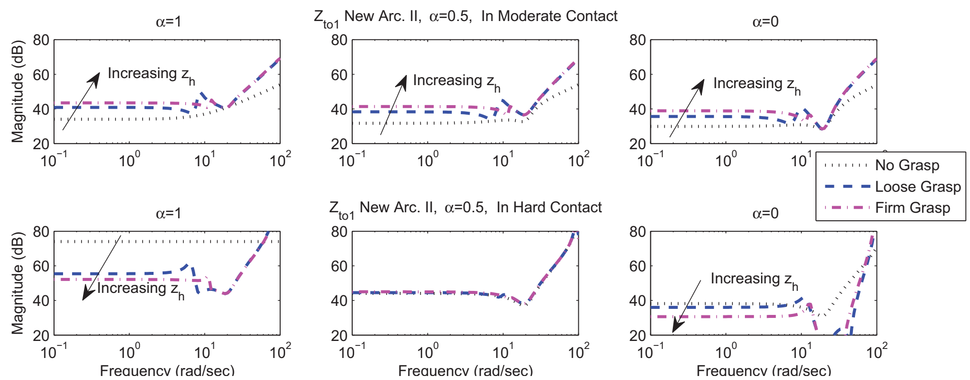
3) Proposed Architecture II: Figure 8(b) shows the effect of operator 2 grasping mode on Z_{to1}, (13), in moderate and hard contact for different values of α in the second new architecture. As it can be seen from Figure 8(b) top row, regardless of the value of α, there is always a large change in the magnitude of Z_{to1} as operator 2 grasping mode changes from no grasp to loose grasp to firm grasp. This can be justified by examining Z_{to1}, (13), in free motion:

$$Z_{to1}|_{Z_e=0} = Z_c || Z_{h2} \quad (16)$$

which is not a function of the dominance factor. Therefore, the effect of operator 2 dynamics on transmitted impedance



(a) Effect of Z_{h2} on Z_{to1} in the proposed architecture I for $n = 3$ in moderate (top row) and hard contacts (bottom row)



(b) Effect of Z_{h2} on Z_{to1} in the proposed architecture II in moderate (top row) and hard contacts (bottom row)

Fig. 8. Effect of operator 2 dynamics (Z_{h2}) on Z_{to1} in (a) the architecture I and (b) the architecture II in moderate and hard contacts for $\alpha = 1, 0.5, 0$.

to operator 1 remains the same for all the values of α. Figure 8(b) bottom row, shows the effect of Z_{h2} on Z_{to1} when the slave robot is in contact with hard environment. The behavior of the system at $\alpha = 0.5$ can be explained by looking at the Z_{to1}, (13), in the extreme cases of environment, as follows:

$$Z_{to1}|_{Z_e \to \infty} = Z_c \frac{2Z_c + 3\alpha Z_{h2}}{3(1-\alpha)Z_c + Z_{h2}} \tag{17}$$

Hence, for $\alpha = 0.5$, $Z_{to1}|_{Z_e \to \infty} = 2Z_c$ which is independent of Z_{h2}. Therefore, as it can be seen from the Figure 8(b) bottom row, when $\alpha = 0.5$ in hard contact, the transmitted impedance to operator 1 is indifferent with respect to Z_{h2} variation.

IV. Experimental Evaluation: User Study

Figure 9 shows a picture of the experimental setup on which the proposed control architectures are implemented. The setup consists of two Quanser 3-DOF Planar Twin Pantograph haptic devices that interface the operators with a simulated model of a 3-DOF Planar Twin Pantograph as the virtual slave, and an LTI mass-damper-spring dynamic model representing a virtual environment. The device can output 3.1 N and 2.3 N in the x and y axes at its tip and torque of 77 $N.mm$ about the z axis. The controller is implemented on a Quad CPU @ 2.4 GHz with sampling rate 1 KHz.

A. Experimental Procedure

A series of tests have been conducted in which a trainer (operator 1) and a trainee (operator 2) collaboratively push the slave robot inside an environment and travel on the oval shape path as shown in Figure 9. The environment is made of pure stiffness with the stiffness of 50 N/m. Six subjects have been selected as trainees while the trainer remained the same. The experiment compares the three different architectures (existing one, and the proposed architectures I and II) in three different operational modes $\alpha = 1, 0.5, 0$. The purpose of this experiment is to investigate whether the user's maneuverability and the sense of environment is improved by switching the architectures at constant α. After the experiment the subjects answered the following questions. In which architecture did you

Q.1. receive a *better sense* of environment?
Q.2. have *more maneuverability* to accomplish the task?
Q.3. receive *better guidance* from the trainer?

Depending on the subjects, the experiments were carried out a number of times, so that the subjects could answer the questions confidently. If the subjects could not prefer one architecture over the other, they could select the best two architectures out of the three or all of them. Figure 10 shows the number of times an architecture was selected by the trainees for each question for specific α.

The bar chart related to question 1 in Figure 10 shows that

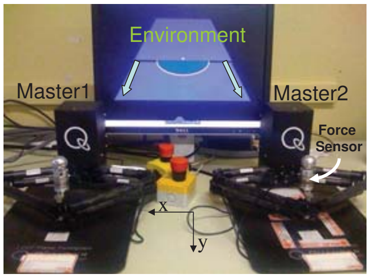


Fig. 9. Picture of the collaborative haptic training experimental setup.

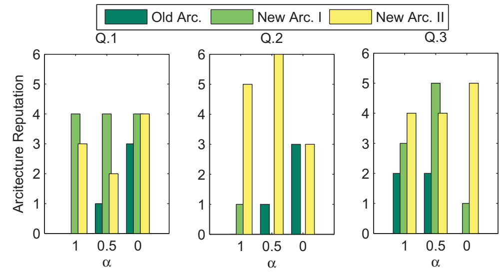


Fig. 10. Experimental evaluation of the proposed architectures: bar chart of the favorite architectures selected by trainee subjects for each question: Q.1 sense of environment, Q.2 maneuverability, and Q.3 guidance reception.

the proposed architecture I always transmits a better sense of environment to the trainees, regardless of their level of authority over the task. This is because of the permanent bilateral connection between the trainee's haptic device and the environment. This can also be seen from Figure 7(b) in which the Z_{to1} has the least variation with changes in α in comparison with other architectures. However, the proposed architecture II is the second favorite architecture among trainees to convey a good sense of environment specially for $\alpha = 1$ and $\alpha = 0$. For $\alpha = 1$, the old architecture was not chosen at all as it does not convey the sense of environment to trianee as discussed in Section II-A.

The bar chart for question 2 shows that the proposed architecture II provides trainee subjects with the best maneuverability and spending less effort to manipulate the environment. However, the old architecture can also provide maneuverability at $\alpha = 0$ for trainee at the cost of cutting off the trainer.

Regarding question 3, once more, the proposed architecture II is the one with the most votes on receiving guidance from trainer for $\alpha = 1$ and $\alpha = 0$. This is because the bilateral connection between the two haptic devices provides users with more maneuverability and ability to receive guidance. However, when both users have the same level of authority over the task, *i.e.* $\alpha = 0.5$, the proposed architecture I is the one that provides slightly better guidance to the trainee. This also can be supported from the sensitivity analysis of Z_{to1} to Z_{h2} in Figure 8, which shows the highest maneuverability of the proposed architecture II. For $\alpha = 0$, the old architecture was not chosen since the trainer's input is blocked.

V. Conclusions and Future Works

In this paper two new control architectures for dual-user haptic training simulation systems have been proposed. The architectures were inspired from the one the authors previously proposed in [1] with substantial improvement in interaction between users and environment, and between the two users. In the proposed architecture I, even though the authority of users over the task is varied depending on their skill level, it always maintains bilateral connection between the two operators and between each operator and the environment. Therefore, the users maneuverability and the sense of environment are increased. In the proposed architecture II, there is always a bilateral connection between the two users which increase the mobility of users regardless of their authority over the task. Additionally, a feedback channel from environment to the users always remains open which grants users a good feel of environment in all values of dominance factor.

The performance of the proposed architectures were numerically and experimentally evaluated under different operating conditions. Kinesthetic performance analysis in terms of transmitted impedance to the operator 1 revealed that the impedance felt by an operator has the least sensitivity to dominance factor variation in the proposed architecture I. This was also yielded from the user study results in which the proposed architecture I remained as the preferred architecture among subjects in conveying a good sense of environment for all values of dominance factor. As it was expected and shown experimentally that the sensitivity of the transmitted impedance to the other operator dynamics, especially in the moderate contact, is more noticeable in the proposed architecture II.

Future works will focus on collecting more extensive data from a larger pool of subjects and investigating the effect of time delay in the communication channel.

References

[1] B. Khademian and K. Hashtrudi-Zaad, "A four-channel multilateral shared control architecture for dual-user teleoperation systems," in *Proc. of IEEE In. Conf. on Intelligent Rob. and Sys.*, pp. 2660–2666, 2007.

[2] B. Khademian and K. Hashtrudi-Zaad, "Performance issues in collaborative haptic training," in *Proc. of the IEEE Int. Conf. on Rob. and Auto.*, pp. 3257–3262, 2007.

[3] S. S. Nudehi, R. Mukherjee, and M. Ghodoussi, "A shared-control approach to haptic interface design for minimally invasive telesurgical training," *IEEE Trans. on Con. Sys. Tech.*, vol. 13, pp. 588 – 592, 2005.

[4] C. R. Carignan and P. A. Olsson, "Cooperative control of virtual objects over the internet using force-reflecting master arms," in *Proc. of IEEE Int. Conf. on Rob. and Auto.*, vol. 2, pp. 1221–1226, 2004.

[5] S. Katsura and K. Ohnishi, "A realization of haptic training system by multilateral control," *IEEE Trans. on Industrial Elec.*, vol. 53, no. 6, pp. 1935–1942, 2006.

[6] S. Moghimi, S. Sirouspour, and P. Malysz, "Haptic-enabled Collaborative Training with Generalized Force and Position Mappings," in *Symp. on Haptic Interfaces for Virtual Env. and Teleoperator Sys.*, pp. 287–294, 2008.

[7] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *Int. J. of Rob. Research*, no. 6, pp. 419–445, 2001.

[8] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. on Rob. and Auto.*, vol. 9, no. 5, pp. 624–637, 1993.

[9] A. Hajian and R. Howe, "Identification of the Mechanical Impedance at the Human Finger Tip," *J. of Biomech. Eng.*, vol. 119, p. 109, 1997.