2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Performance Issues in Collaborative Haptic Training

Behzad Khademian and Keyvan Hashtrudi-Zaad

Abstract— **This paper proposes a new multilateral position-position shared control architecture for dual-user haptic training. The proposed controller allows interaction between both users, the trainee and the trainer, as well as between the users and the virtual slave robot and environment. It also allows for the adjustment of the dominance of the trainer over the trainee in interaction with the virtual slave and environment through a dominance factor parameter. The issue of transparency in such collaborative haptic simulation system has been discussed. A performance index has also been defined to quantify the users' skill for a specific task under study. This metric is used to identify the maximum allowable dominance of the trainee over the trainer. Haptic simulation experiments have been carried out with two Planar Twin Pantograph haptic devices and a simulated pantograph as the slave robot.**

I. INTRODUCTION

The vast majority of existing telerobotic and haptic applications involve an operator (user) at one end and a real or virtual environment at the other end interacting with each other [1]. Emerging applications of haptic technology are in *human haptic guidance* for rehabilitation [2] and surgical training [3] in which two users interact with each other via two haptic interfaces and a shared real or virtual environment.

Haptic controllers are designed to obtain stability and transparent performance. Transparency is a condition, at which the operator feels like physically being at the virtual site and performing the task directly. For single-master/single-slave (or environment) haptic systems, transparency is quantitatively defined as matching between the impedance transmitted to the operator and the environment impedance [4]. Sirouspour generalized the concept of transparency for multiuser teleoperation systems by introducing a desired virtual cooperative tool impedance, which allows the adjustment of the impedances felt by the users [5]. As it will be shown in this paper, the conventional definition of transparency is no longer applied to dual-user collaborative haptic systems, since one operator sees not only the environment impedance but also the other operator's impedance. In this paper, we tackle the issue of transparency in a dual-user collaborative haptic system by calculating the transmitted impedance to each operator.

There has been a number of control architectures proposed for multi-master/multi-slave teleoperation or haptic systems [2], [5], [6], [7]. Sirouspour in [5] proposed a four-channel μ-synthesis-based control architecture to control multiple slave robots holding a common tool for manipulating an environment [5]. The closed kinematic chain formed by the slave robots and the tool imposes constraints on the motion of the slaves. In [7], a two-channel multilateral position-position adaptive controller has been introduced. However, no user study results on control share or users dominance have been reported in these works.

In [6], Nudehi *et al.* proposed a shared control strategy for haptic collaboration between a trainer and a trainee in performing tele-surgery using H-∞ control method. In their architecture, the slave robot is controlled unilaterally and no kinesthetic feedback is provided to the users from the slave. In the cooperative architecture developed in [2], both master robots are independently interacting with the virtual object, which is considered as the slave.

As opposed to [2] and [6], the multilateral control architecture proposed in this paper is designed for direct interaction between the two users (trainer and trainee) as well as between the users and the environment through the two masters and slave robots. The shared nature of the proposed controller makes collaboration between the two users easy in such a way that a user can have no, partial or full control over the slave movement in the environment and can also affect the other user movement at the same time. The kinesthetic feedback from slave robot to both users help the users to feel the environment. As in [6], a *dominance factor* controls the supremacy of each user's authority over the slave robot and can be set based on the skill of the users. To quantify users' skill, a suitable performance index is defined with regard to the designed experiment. Experiments are carried out on a dual-user haptic simulation system including two three degree-of-freedom (3-DOF) Planar Twin Pantograph haptic devices interfacing trainer and trainee and a simulated pantograph as the slave robot performing tasks in a shared virtual environment. The data collected from user study experiments for path following task with six trainee subjects are employed to quantify the trainees' skills and to determine the minimum dominance factor to set for each trainee.

This paper is organized as follows. The proposed shared control architecture for a dual-user haptic system is introduced in Section II. Transparency performance analysis is presented in Section III. The path following skill of six subjects are quantified in Section IV. Finally some concluding remarks are given in Section V.

II. COLLABORATIVE HAPTIC SIMULATION SYSTEM

A. Multilateral Shared Control Architecture

The proposed multilateral position-position shared control architecture is shown in Figure 1 in which the operator1 is

---

This work was supported by PRECARN, Ontario Centres of Excellence (OCE), and Natural Sciences and Engineering Council of Canada (NSERC).

The authors are with the Department of Electrical and Computer Engineering, Queen's University, Kingston, ON K7L 3N6, Canada `5bk@qlink.queensu.ca, khz@post.queensu.ca`.

1-4244-0602-1/07/$20.00 ©2007 IEEE.

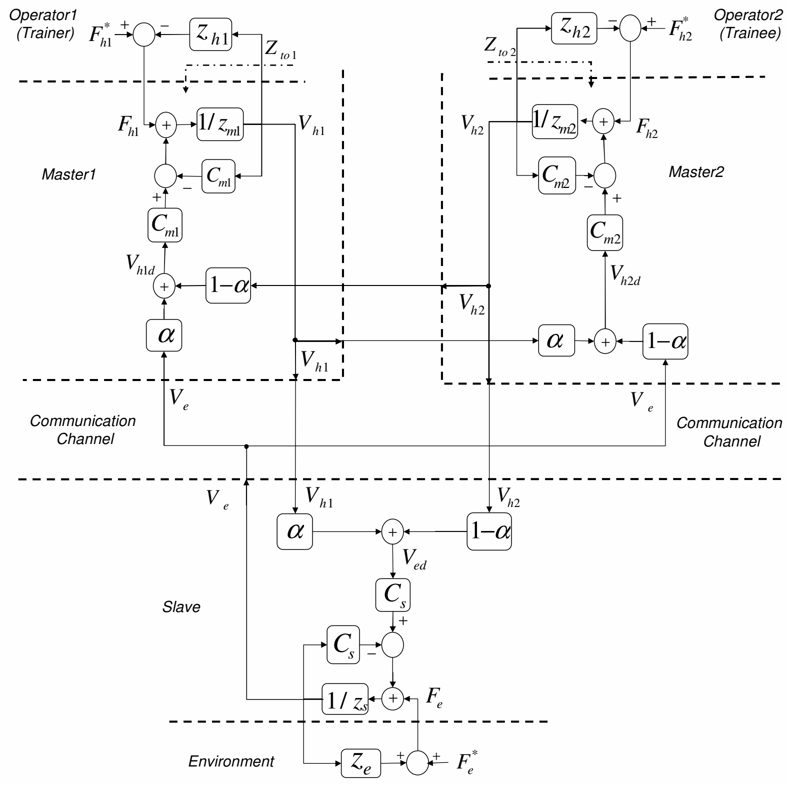

Fig. 1. Block diagram of the proposed multilateral position-position shared control architecture.

the trainer and operator2 is the trainee. The operators and the environment are modeled around their operating points with one-port networks, exhibiting Linear-Time-Invariant (LTI) dynamics:

$$F_{h1} = F_{h1}^{*} - Z_{h1}V_{h1} \quad (1)$$

$$F_{h2} = F_{h2}^{*} - Z_{h2}V_{h2} \quad (2)$$

$$F_{e} = F_{e}^{*} + Z_{e}V_{e} \quad (3)$$

where Z_{h1}, Z_{h2}, and Z_e are the operators and environment impedances, V_{h1}, V_{h2} and V_e are operators and environment positions[1], F_{h1}, F_{h2}, and F_e are the operators forces applied to the master robots and the slave force exerted on the environment, and F_{h1}^{*}, F_{h2}^{*} and F_e^{*} are the exogenous force inputs generated by the operators and the environment, respectively.

The master and slave robots are modeled by LTI two-port networks. The dynamics of the masters and slave in Laplace domain, assuming that the operators are interfaced with the masters and the slave is in contact with the environment, are expressed as:

$$Z_{m1}V_{h1} = F_{h1} + F_{cm1} \quad (4)$$

$$Z_{m2}V_{h2} = F_{h2} + F_{cm2} \quad (5)$$

$$Z_{s}V_{e} = -F_{e} + F_{cs} \quad (6)$$

where $Z_{m1} := M_{m1}s$, $Z_{m2} := M_{m2}s$ and $Z_s := M_s s$ represent the LTI mass models of force actuated master and slave manipulators, and F_{cm1}, F_{cm2} and F_{cs} are the control commands. For a position-position two-channel multilateral controller:

$$F_{cm1} = C_{m1}(V_{h1d} - V_{h1}) \quad (7)$$

$$F_{cm2} = C_{m2}(V_{h2d} - V_{h2}) \quad (8)$$

$$F_{cs} = C_{s}(V_{ed} - V_{e}) \quad (9)$$

where $C_{m1} := B_{m1} + \frac{K_{m1}}{s}$, $C_{m2} := B_{m2} + \frac{K_{m2}}{s}$ and $C_s := B_s + \frac{K_s}{s}$ denote the local position PD controllers, and V_{h1d}, V_{h2d}, and V_{ed} are the desired positions for masters and slave robots transmitted through the communication channel. In our proposed shared control architecture, the masters and slave are interconnected and the desired position commands V_{h1d}, V_{h2d}, and V_{ed} are shared between the positions of the other two robots, that is

$$V_{h1d} = \alpha V_{e} + (1-\alpha)V_{h2} \quad (10)$$

$$V_{h2d} = (1-\alpha)V_{e} + \alpha V_{h1} \quad (11)$$

$$V_{ed} = \alpha V_{h1} + (1-\alpha)V_{h2} \quad (12)$$

---

[1] Since impedance is expressed as the ratio of force to velocity, kinematic variables including position, velocity, and acceleration are collectively shown by V and referred to as position.

where α is the *dominance factor*, and $\alpha \in [0\,1]$. The control authority of operator1 (trainer) and operator2 (trainee) over the slave robot are determined by α and $1-\alpha$, respectively.

Substituting (10)-(12) in the control commands (7)-(9) and using the resulting commands in (4)-(6), the masters and slave closed-loop dynamics can be expressed as:

$$F_{h1} = Z_{cm1}V_{h1} - (1-\alpha)C_{m1}V_{h2} - \alpha C_{m1}V_e \quad (13)$$

$$F_{h2} = Z_{cm2}V_{h2} - \alpha C_{m2}V_{h1} - (1-\alpha)C_{m2}V_e \quad (14)$$

$$F_e = -Z_{cs}V_e + \alpha C_s V_{h1} + (1-\alpha)C_s V_{h2} \quad (15)$$

where $Z_{cm1} := Z_{m1} + C_{m1}$, $Z_{cm2} := Z_{m2} + C_{m2}$, and $Z_{cs} := Z_s + C_s$ are the dynamics of the PD controlled master and slave robots.

B. User Dominance in Shared Environment

The proposed architecture is designed for training purposes, so that the trainer can control the trainee's movement and the trainee can feel the trainer's commands through his/her haptic device. The users can also have no, partial or full control over the slave robot. These features are realized by introducing the dominance factor, α, which determines the supremacy of the users over the slave robot and over each other.

When $\alpha = 1$, $V_{h1d} = V_e$ and $V_{ed} = V_{h1}$; thus, master1 and slave form a position-position two-channel bilateral control system [8]. Since $V_{h2d} = V_{h1}$, the motion of the trainee (master2) is fully controlled by the trainer (master1). This case is called *training mode*. When $\alpha = 0$,in a dual manner, master2 and slave form a bilateral two-channel control system and the trainee (master2) has full control over the trainer (master1). In this mode, the trainer is dragged by the trainee, which is suitable for evaluating the trainee's *performance*. If α is between zero and unity, both users can control the slave robot and the trainer can *guide* the trainee to perform a task collaboratively in a shared environment. A value of α between zero and unity can be allocated to trainee based on the trainee's skill on performing a specific task. The difference between the shared control architecture in [6] and the one we proposed is that, in [6] there is no kinesthetic force feedback from the environment and in the extreme case of $\alpha = 1$, the trainer cannot drag the trainee.

III. PERFORMANCE ANALYSIS: TRANSPARENCY

Based on the Lawrence definition of transparency a single-master/single slave teleoperation system is said to be transparent if the impedance transmitted to or felt by the operator equals to the environment impedance (when environment exogenous input is nulled) [4]. In this section we analyze transparency for collaborative haptic simulation system, in which two users simultaneously perform on the same task in a shared virtual environment. In such systems one operator feels not only the environment impedance but also the impedance of the other operator. In the proposed architecture, as shown in Figure 1, transmitted impedances to the operators, Z_{to1} and Z_{to2}, are defined as:

Impedance $Ms+B+\frac{k}{s}$	M Kg	B $Nsec/m$	K N/m
Environment Impedance			
Soft Z_e	0.1	1	1
Medium Z_e	1	10	100
Hard Z_e	1	100	10000
Hand Impedance Z_{h1} and Z_{h2}	1	10	100
Robot Impedance Z_{m1} , Z_{m2}, and Z_s	0.2	0	0
Position Controller C_{m1} , C_{m2}, and C_s	0	2	10

TABLE I

PARAMETERS VALUE OF IMPLEMENTED MULTILATERAL CONTROL ARCHITECTURE.

$$Z_{to1} := \frac{F_{h1}}{V_{h1}}\Big|_{F_e^*=0,F_{h2}^*=0} \quad (16)$$

$$Z_{to2} := \frac{F_{h2}}{V_{h2}}\Big|_{F_e^*=0,F_{h1}^*=0} \quad (17)$$

And after some calculation, the transmitted impedances Z_{to1} and Z_{to2} can be expressed as follows:

$$Z_{to1} = Z_{cm1} - \frac{\alpha^2 C_{m1}C_s}{Z_e+Z_{cs}} - \frac{\alpha(1-\alpha)C_{m1}C_{m2}}{Z_e+Z_{cs}} \times \frac{(Z_{cs}+Z_e+\alpha C_s)((1-\alpha)C_s+Z_e+Z_{cs})}{(Z_e+Z_{cs})(Z_{cm2}+Z_{h2})-(1-\alpha)^2C_{m2}C_s} \quad (18)$$

$$Z_{to2} = Z_{cm2} - \frac{(1-\alpha)^2 C_{m2}C_s}{Z_e+Z_{cs}} - \frac{\alpha(1-\alpha)C_{m1}C_{m2}}{Z_{cs}+Z_e} \times \frac{(Z_{cs}+Z_e+(1-\alpha)C_s)(\alpha C_s+Z_e+Z_{cs})}{(Z_e+Z_{cs})(Z_{cm1}+Z_{h1})-\alpha^2C_{m1}C_s} \quad (19)$$

For $\alpha = 1$, when the trainer is fully dominant over the trainee and the slave robot, the transmitted impedances, Z_{to1} and Z_{to2} are simplified to:

$$Z_{to1}|_{\alpha=1} = Z_{cm1} - \frac{C_{m1}C_s}{Z_e+Z_{cs}} \quad (20)$$

$$Z_{to2}|_{\alpha=1} = Z_{cm2} \quad (21)$$

In this situation, as mentioned before, master1 (trainer) and the slave form a two-channel bilateral system and (20) is the transmitted impedance for such systems. On the other hand master2 does not affect the closed-loop dynamics of master1 in (13) thus master1 position V_{h1} acts as an exogenous desired command for master2 in (14), which is nulled for $F_{h1}^* = F_e^* = 0$ when deriving Z_{to2}. Therefore, the only impedance that master2 experiences is the closed-loop dynamics of the position controlled master2, *i.e.* Z_{cm2}. In other words, the trainee does not see master1, Z_{h1}, and the environment, Z_e, at all. When $\alpha = 0$, the transmitted impedances become:

$$Z_{to1}|_{\alpha=0} = Z_{cm1} \quad (22)$$

$$Z_{to2}|_{\alpha=0} = Z_{cm2} - \frac{C_{m2}C_s}{Z_e+Z_{cs}} \quad (23)$$

which in this case, due to the lack of mutual interaction between the trainer and the trainee, the trainer only feels his/her device impedance. This situation is dual to the previous case, *i.e.* $\alpha = 1$.

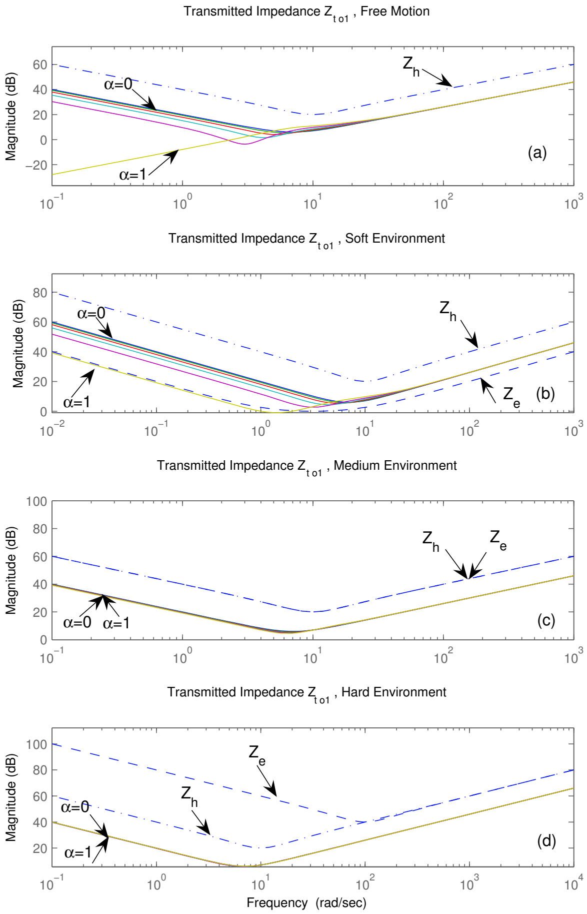

Fig. 2. Bode diagram of Z_{to1} for operation in (a) free motion, and on (b) soft, (c) medium and (d) hard environments, for $\alpha = 0, 0.2, 0.4, 0.6, 0.8, 1$.

When $\alpha \in (0\ 1)$, as it can be implied from (18) and (19), each operator sees not only his/her device impedance and environment impedance but also impedance of the other operator. Figure 2 shows the bode diagram of the transmitted impedance Z_{to1}, with various α when slave is in free motion or in contact with soft, medium or hard environments. Table I shows the parameter values used in the simulation. The masters and slave control parameters are selected such that their closed-loop dynamics have fastest non oscillatory response. The operators impedances $Z_{h1} = Z_{h2}$ represent the typical dynamics of a human arm with moderate muscle contraction [9]. 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.* $Z_{to1}(\alpha) = Z_{to2}(1-\alpha)$. Therefore, we only focus on one transmitted impedance, that is Z_{to1}.

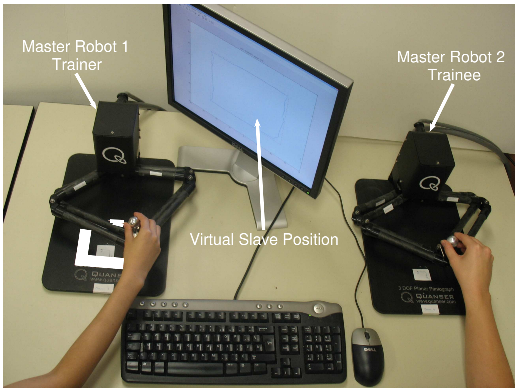

Fig. 3. Picture of the collaborative haptic training experimental setup.

As it can be seen from Figure 2, at low to mid frequencies, when the slave robot is in free motion, the nature of transmitted impedance changes from stiffness to mass as α increases from 0 to 1. This is attributed to the term $\frac{C_{m1}C_s}{Z_{cs}}$, which almost nulls Z_{to1} in (20). For $0 < \alpha < 1$, the transmitted impedance Z_{to1} is also affected by Z_{h2}, the operator2 impedance. When interacting with environment, especially the harder ones, the effect of changing α vanishes and the transmitted impedance for different values of α becomes the same. This is because as the environment impedance grows

$$Z_{to1} \rightarrow Z_{cm1} - \frac{\alpha(1-\alpha)C_{m1}C_{m2}}{Z_{cm2}+Z_{h2}} \quad as\ |Z_e| \rightarrow \infty \tag{24}$$

Since $|Z_{h2}| >> |Z_{cm2}|$ and in low to mid frequencies $\frac{|C_{m1}C_{m2}|}{|Z_{h2}|} \approx 1 << |Z_{cm1}|$, thus $Z_{to1} \rightarrow Z_{cm1}$ and the transmitted impedance becomes independent of α.

For high frequencies (above 10 Hz), Z_{to1} is dominated by:

$$Z_{to1}|_{highfreq.} \approx M_{m1}s \tag{25}$$

In this case, again as can be seen from Figure 2, the transmitted impedance becomes independent α.

IV. HAPTIC GUIDANCE EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

A. Experimental Setup and Procedure

In this section, the performance of the proposed collaborative haptic controller is experimentally evaluated for a specific task of following a square path. The proposed multilateral shared controller is implemented on a dual-user haptic simulation system consisting of two 3-DOF Planar Twin Pantograph haptic devices that interface the users with a simulated model of 3-DOF Planar Twin Pantograph as the virtual slave, and an LTI mass-damper-spring dynamic model representing a virtual environment (Figure 3). A series of tests are conducted in which the trainer (operator1) teaches the trainee (operator2) how to lead the slave robot to follow a $100 \times 100mm$ square path. During the test only the trainer is able to see the desired square path and the actual track of the slave. This privilege grants operator1 with an extra knowledge set that a trainer needs when interacting with trainees. The trainee only knows from where to start. The dominance factor is set by the trainer in the order of $\alpha = 1, 0.75, 0.5, 0.25, 0$, signifying a shift of dominance from

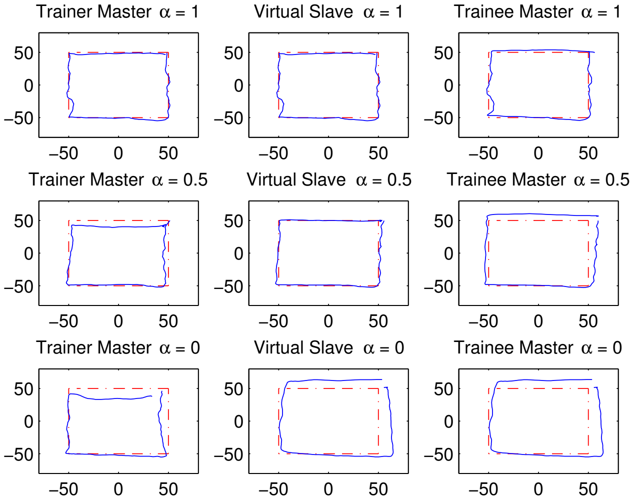

Fig. 4. The trainer master, the trainee master and the virtual slave positions (solid line) traversing the desired square path (dash line).

the trainer to the trainee. Six subjects have been selected as trainees, while the trainer remained the same for all experiments. The above sequence of experiments has been followed four times for each trainee subject.

B. *Human Haptic Guidance Experiment*

Figure 4 shows one loop of the path followed by the trainee, the trainer and the slave in solid lines for different values of the dominance factor. When $\alpha = 1$ (training mode), the virtual slave robot and the trainee receive command only from the trainer. However, the slave robot is in interaction with the trainer, not the trainee, and trainee is only dragged by the trainer (top figures in Figure 4). By decreasing α to 0.5 (guidance mode), the trainer and the trainee have balanced dominance on the slave. As it can be seen from the middle figures, the trainer corrects the trainee's movement to make the virtual slave robot follow the square path faithfully, by pulling his/her master robot in the opposite direction (inside the square) of the trainee's master motion . In this case, both operators experience the same feel of the environment. To give full authority to the trainee, α is changed to 0 (evaluation mode). Therefore, the trainee becomes dominant over the the slave robot that receives command only from the trainee. As a result, the slave follows the path very poorly. Although the trainer tries to over compensate by pulling its master robot deep inside the square, the trainer's movement does not have any effect on the trainee's motion (bottom row in Figure 4), since it is the trainee who drags the trainer.

C. *Task-based Performance Evaluation*

Figure 5 shows the workspace of the pantograph. The robot should move on the black solid square. To calculate the error the following strategy is applied. Depending on the position of the robot end-point denoted by (P_x, P_y) in any of the areas 1 to 5, the tracking error is derived from

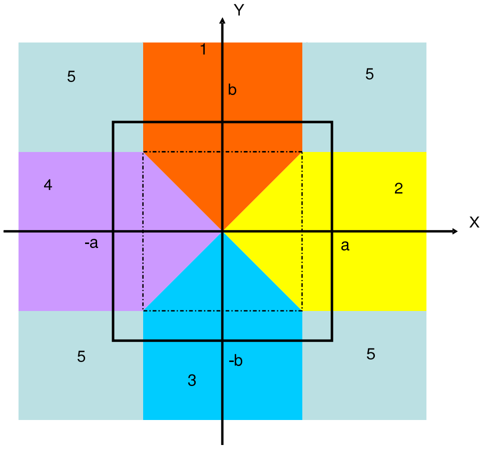

Fig. 5. Workspace of the Planar Twin Pantograph.

$$e = \begin{cases} |b - P_y| & area1 \\ |a - P_x| & area2 \\ |-b - P_y| & area3 \\ |-a - P_x| & area4 \\ e_d & area5 \end{cases} \tag{26}$$

where $a = b = 50\,mm$, and e_d is the Euclidean distance between the robot's position and the corresponding desired square path corner in area 5. The dash line inner square in Figure 5 specifies the borders between different areas within the square. The size of the inner square is selected such that the horizontal and vertical distance between the two squares be $5\,mm$.

To quantify performance for our specific task, the following performance index is defined:

$$J(\alpha) = \frac{\frac{1}{n}\sum_{n}^{i=1} e_i}{l} \tag{27}$$

where e_i is the error at each sample point i, l is the length of the traversed path by the robot end-effector, and n is the number of samples. J is calculated after each trail for each α. Since each trail is done four times for each α, the average value of J is computed.

Figure 6 shows the average performance index J for the trainer's robot, the slave robot, and the trainee's robot for all the six trainee subjects. The following points can be deducted from Figure 6:

- For all subjects, transferring authority from trainer to trainee increases performance index, J.
- The slave performance index in the middle figure, quantifies the skill of the subjects for the specific path following task. For example, subject 5 demonstrates the worst performance while subject 1 is the most skillful.
- Since all experiments are run with the same trainer, the performance indices are very close when dominance is fully transferred to the trainer.
- By looking at the slave performance index, the *critical* dominance factor, α_c, is defined as the dominance

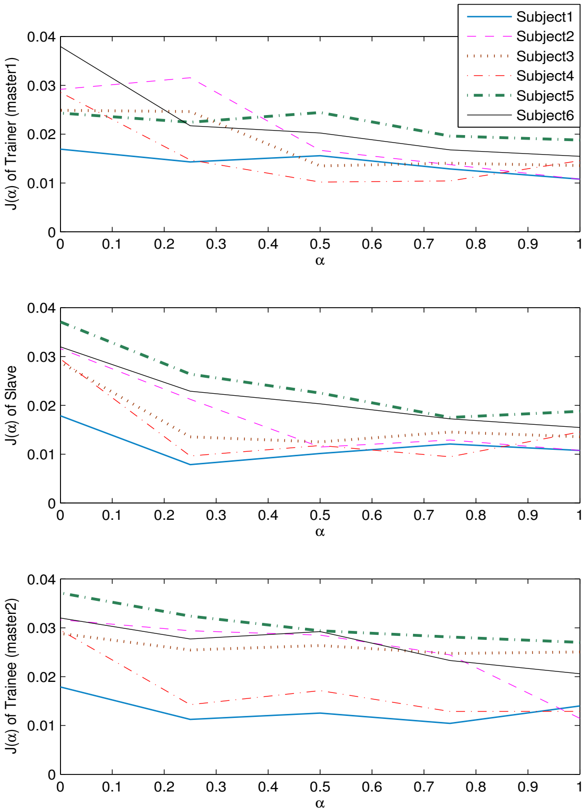

Fig. 6. Average performance indices of trainer, trainee and slave for experiments with six trainee subjects.

factor at which the performance index ramps up. In other words, α_c is the minimum dominance factor that can be assigned to a trainee to assure a good slave performance with respect to the performance range of that trainee. For subjects 1 to 6, the value of α_c is 0.75, 0.5, 0.75, 0.75, 0.25, 0.25, respectively.

- Decreasing α (transferring authority to trainee) not only causes generating higher performance indices for the slave and the trainee, but also causes the trainer to have poor performance. This is because of the trainer's compensating movement to correct the slave path.
- Making the slave robot follow the path closely, does not necessitate position matching between the masters and slave. Hence, the conventional force and position matching definition for transparency is not desired for this particular task.

The proposed haptic controller has application in surgical training in which a trainer can teach his/her trainees to perform a task in a virtual environment via two haptic devices. The dominance factor, α, has an important role in guiding the trainee for better task performance. Having done the training procedure with $\alpha = 1$, depending on the trainee's skill, the experienced surgeon can set the dominance factor to a suitable value and allow the trainer to perform the task in a collaborative environment. One can find a suitable value for α by looking at the slave performance index profile and selecting the critical value α_c, which provides the best trade-off between performance and the level of authority for the corresponding trainee.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a novel position-based multilateral shared control architecture has been proposed and implemented on a dual-user haptic training system. The controller has been designed such that it allows for interaction between both users and between the users and the virtual slave robot interacting with a virtual environment. It also allows for the adjustment of the trainer's dominance over the trainee through a dominance factor parameter. The analysis of transparency for the dual-user collaborative haptic system has revealed that the transmitted impedance to each operator is not only affected by the environment impedance, but also by the other operator impedance as well. This prompts the need for a new definition of transparency for such systems, which may also depend on the task at hand.

An experimental user study with six trainee subjects has also been conducted to evaluate the trainees skills in controlling the virtual slave in a shared environment. The experimental results with a spatial performance index designed for the specific path following task pointed at a critical dominance factor, for each trainee subject, below which the performance index ramps up. This point of deflection determines the maximum allowable dominance of the trainee over the trainer for good performance considering the performance range of that trainee.

Future work will focus on the use of filters rather than scalar for the dominance factor and the implementation of other haptic control architectures such as force-position and four-channel for improved transmitted impedance.

REFERENCES

[1] S. E. Salcudean, "Control of teleoperation and haptic interfaces," *Control Problems in Rob. and Auto., Springer-Verlag LNCIS-230*, pp. 51–66, 1997.

[2] 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.

[3] B. Chebbi, D. Lazaroff, F. Bogsany, P. X. Liu, L. Ni, and M. Rossi, "Design and implementation of a collaborative virtual haptic surgical training system," in *Proc. of IEEE Int. Conf. on Mechatronics and Auto.*, vol. 1, pp. 315–320, 2005.

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

[5] S. Sirouspour, "Modeling and control of cooperative teleoperation systems," *IEEE Trans. on Rob.*, vol. 21, no. 6, pp. 1220–1225, 2005.

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

[7] S. Sirouspour and P. Setoodeh, "Multi-operator/multi-robot teleoperation: an adaptive nonlinear control approach," in *Proc. of IEEE/RSJ Int. Conf. on Intelligent Rob. and Syst.*, pp. 1576–1581, 2005.

[8] G. J. Raju, G. C. Verghese, and T. B. Sheridan, "Design issues in 2-port network models of bilateral remote manipulation," in *Proc. of IEEE Int. Conf. on Rob. and Auto.*, pp. 1316–1321, 1989.

[9] F. Mobasser and K. Hashtrudi-Zaad, "A method for online estimation of human arm dynamics," in *Proc. of IEEE Int. Conf. of Engineering in Medicine and Biology Society*, pp. 2412–2416, 2006.