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SHARED CONTROL FOR UPPER-EXTREMITY REHABILITATION IN VIRTUAL ENVIRONMENTS

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ABSTRACT

Interest in the rehabilitation applications for robots has been increasing. For example, various devices have been developed to aid in reaching movements of stroke, traumatic brain injury (TBI), and spinal cord injury (SCI) patients. Typically these devices provided guided reaching movements for elbow and shoulder. The robotic aspect allows for repeatability, along with additional data for post-session analysis. To date, robotic rehabilitation systems with haptic feedback have not fully exploited the capabilities of a haptic display device. The simulators primarily focus on obeying the physical laws that govern such systems in order to re-create realistic environments for rehabilitative tasks, or the robotic devices are employed only for their ability to carry the impaired limb through various trajectories. This paper will present a novel active assistance paradigm for interactions in virtual environments displayed via haptic interfaces. The author's recent research efforts have focused on the design of perceptual overlays in virtual environments that are active rather than passive. Passive virtual fixtures have been the primary perceptual overlay in haptics, and have been used extensively as "virtual rulers" in teleoperation environments to improve operator performance of pick-and-place tasks. Active assistance in the form of shared control between the haptic device and the human operator has the potential to elicit even better performance in virtual and remote environment interactions, and also has implications for improving training effectiveness. The intended applications include stroke rehabilitation and training for pilots, manufacturing, and surgery. A description of perceptual overlays and details of the shared control paradigm are presented, along with results from some preliminary experiments on shared control haptic assistance for training in virtual environments.

INTRODUCTION

The addition of haptic feedback to virtual environment simulations and telerobotic systems is known to provide benefits over visual-only displays such as reduced learning times, improved task performance quality, increased dexterity, and increased feelings of realism and presence [1-7]. Haptic feedback in virtual environments also enables a wider range of applications, including manipulation and assembly tasks where force cues are necessary and medical applications such as training for palpation, needle insertion, minimally invasive surgery, and rehabilitation [8]. To date, however, virtual environment systems with haptic feedback have not fully exploited the capabilities of a haptic display device. The simulators primarily focus on obeying the physical laws that govern such systems in order to re-create realistic environments for assembly, surgery, flight, and other procedures. The addition of haptic virtual cues and active assistance from the device, not realized in the physical world, could dramatically increase the amount of information that can be conveyed to a user, ideally improving performance in the virtual environment, or improving the effectiveness of a haptic training or rehabilitation system.

This paper presents a shared control interaction paradigm for haptic interface systems. In terms of performance enhancement, shared control between a human and a robotic interface can boost performance because the robot can control low-level functions (reducing oscillation or tremor, force management, obstacle avoidance, or control of orientation) while the human operator maintains high-level control such as path planning and position control. The area of teleoperation has seen much activity in shared control, as researchers implement these partitioning techniques. This approach to human-robot interaction exploits the pros of each system for the betterment of overall performance. Alternately, the robotic device can concurrently share execution of the task without dividing high- and low-level actions between the user and shared controller. In addition to performance enhancement during haptic virtual environment interactions, the shared control paradigm has implications for improving training effectiveness by reducing learning times and improving retention of manual skills, and has benefits over existing interaction paradigms. The application to training (and subsequent implications for rehabilitation) will be the focus of this paper. Such implementation of shared control has not been reported in the literature, and therefore this paper summarizes novel pilot experiment results that address the use of shared control in virtual environments to improve training effectiveness.

The remainder of the paper is organized as follows: First the author provides a thorough literature review, which is necessary to define the proposed shared control approach in relation to prior approaches for performance enhancement and training in haptic virtual environments. The next section describes the proposed shared control paradigm, with a focus on prior instances of shared control and a description of three proposed shared interaction architectures for performance enhancement and training in haptic virtual environments. Experimental results for training in virtual environments with shared control are presented. Finally, conclusions and implications for future work are given.

PRIOR WORK

Most efforts to incorporate haptic feedback for performance enhancement, training, and rehabilitation have focused on three approaches. In the first approach, the haptic device is used to produce virtual force fields or fixtures in order to show the human user where not to go in the virtual environment. These passive guides are only perceived by the user when forbidden regions of the workspace are explored. In the second approach, the human user remains passive while the robotic device controls movement of the hand or arm. These examples are most prevalent in rehabilitation, where the subject may have limited use of an impaired limb, and requires the robot to perform the reaching motions on behalf of the patient. The act of being carried through desired trajectories has benefit to patients suffering from stroke [9]. The third approach, primarily for the purpose of training with haptic devices, is a record and replay strategy. Here, an expert's interactions with a virtual environment are recorded, and then in subsequent trials, a novice user feels the desired motion and then attempts to mimic it without haptic feedback.

The idea of shared control between humans and robots for performance enhancement and training is a relatively novel research thrust. This section will review advances in the related areas of passive haptic assistance for performance enhancement and training and robot-assisted rehabilitation in order to lay a foundation for the remainder of the paper.

Passive assistance for performance enhancement

Some prior work has addressed the addition of physically non-realizable virtual cues in haptic environments, both virtual and remote. For example, Rosenberg introduced the notion of virtual fixtures as perceptual overlays for enhanced operator performance in telemanipulation tasks [10]. In Rosenberg's work, the virtual fixture was a simulated surface which prevented hand motion beyond the surface thus guiding the user to follow the trajectory defined by the extents of the virtual fixtures. In this case, the fixtures were present throughout the duration of the teleoperation task. Because the user would always interact with the remote environment via the force-feedback interface, the virtual fixtures could be permanently overlaid on the display. A similar application is the use of virtual fixtures in a refueling task [11].

In the case of haptics for training applications however, the trainee must learn how to interact with the simulated environment with the end goal being unassisted interaction with a real environment. Therefore, virtual fixtures may be helpful in training, but Rosenberg's fixtures were either "on" or "off" and appeared in fixed locations with fixed parameters for force output calculation during interaction. An "on" or "off" approach to the use of virtual fixtures in training may improve performance during training, but performance in a "real-world" task may be in fact worse since the subject has learned to rely on the presence of the virtual fixtures in the virtual training environment. This phenomenon has been seen when augmented feedback such as computer enhancement of the environment has been added to a graphics-only virtual environment [12].

Another example of virtual fixtures was presented by Bettini and others for use as manipulation assistance for interactive tasks between humans and robots [13]. They implemented soft constraints in order to allow the user to maintain more control of device positioning. The system used vision to sense a desired path in a plane, and the robot encouraged motion toward and along the path using a direction-based control law. As with virtual fixtures for teleoperated tasks, the virtual fixtures implemented with the steady-hand robot system can remain present for all interactions with the system, since the target tasks will be performed using the robot for assisted manipulation.

Passive assistance for training – record/replay

Several researchers have sought to use haptic devices as virtual teachers. In these instances, desired trajectories or interaction forces are programmed or recorded during an initial trial. Then, the end user begins a training session where this desired trajectory or force information is played back. Gillespie et al. used this method to display the optimal trajectory for balancing an inverted pendulum attached to a 1 degree-of-freedom cart in the shortest possible amount of time [14]. Subjects felt the optimal trajectory of the cart and then attempted to play back the motion after the teaching portion of the simulation was completed. The subjects remained passive during the teaching phase of the experiment. Likewise, the virtual teacher was not active during the trainee's execution of the pendulum balancing task.

Other work has attempted to record and subsequently playback both position and force information to the trainee [15-18]. While these attempts succeed in displaying both position and force information, all were based on a record and replay strategy. With this approach, the subject passively felt the desired interaction modes and then, without artificial cues, tried to recreate the virtual teacher's methods. Specific outcomes for work by Huang and Gillespie included improved human performance of a ball and beam balancing task with haptic feedback during the demonstration sessions [18]. While these methods may be successful for training, they do not take advantage of a dynamic interaction between the human and haptic device.

Robot-assisted rehabilitation

Along the lines of training, haptic assistance has also been implemented in robotic rehabilitation systems. Burgar and his colleagues have studied the ability of a device (Mirror-Image Movement Enabler - MIME) to assist limb movements and facilitate recovery of motor function in subjects with chronic hemiparesis due to stroke [19]. MIME incorporates an industrial robot and operates in three unilateral modes and one bimanual mode. In unilateral operation, passive, active-assisted, and guided movements against a resistance are possible. The MIME system's novel bimanual mode allows subjects at any impairment level to practice and complete mirror-image bimanual movements, where the unimpaired limb defines the trajectory along which the robot will carry the impaired limb.

An example of active assistance for upper limb rehabilitation, implemented by Mussa-Ivaldi and Patton, used perturbing force fields during arm motion to elicit desired after effects as subjects attempt to overcome the perturbations and move to a target in space [20-22]. This technique, while similar to the proposed method in this paper for shared control, does not simultaneously display a virtual environment, and it relies on perturbation and after effects, rather than displaying desired motion directly. Reinkensmeyer and colleagues have also implemented a form of perturbing force fields in the form of transient dynamic amplification [23]. They concluded that motor learning of a novel dynamic environment was accelerated by exploiting the error-based learning mechanism of internal model formation. However, they also concluded that nonlinearities in adaptive response may limit the feasible acceleration of this learning. Their work suggests that movement training devices may benefit from amplification (as opposed to reduction) of movement errors. This finding is contradictory to findings of the author [24] that indicate that passive and active assistance during training, which ultimately reduces error amplitudes, may improve motor training effectiveness. The primary difference between the implementations of [23] and [24] can be summarized in the implementation of the assistance functions. In the error amplification work, healthy subjects are asked to complete stepping motions in a novel dynamic environment. In the case of haptic assistance for error reduction during training, subjects are attempting to learn control of an underactuated dynamic system. This paper will present the haptic assistance paradigm, results for training of a dynamic task with haptic assistance, and implications of the findings for training and rehabilitation.

SHARED CONTROL

Communication between two humans sharing a physical task can take many forms, including verbal, gestures, or physical interaction. A recent study by Reed and colleagues studied human-human cooperation in a dynamic task [23]. They hypothesize that a significant amount of communication should be transferred through force and motion, applied directly or through a mutually held object. Similarly, work by Gillespie and his colleagues studied virtual teacher models for the acquisition of sensorimotor skills [14]. They study three paradigms for teacher-pupil interaction with an implement, namely indirect contact (via the implement), double contact (pupil grasps implement, teacher grasps pupil), and single contact paradigm (teacher grasps implement, pupil grasps teacher). All paradigms were successful in relaying the optimal strategy for task completion.

The author's proposed shared-control algorithm approach for human-robot interaction is similar to the double-contact paradigm represented in Figure 1 and discussed by Gillespie et al., where the novice will interact both with the virtual environment and with the expert via force feedback contributions from both sources. In the system shown, the human operator senses a dynamic virtual task, while at the same time experiencing active feedback generated by the shared controller. This is represented by the block diagram in Figure 2. The total force feedback command to the human operator is based on the physics of the virtual environment that is being displayed combined with the effect of the shared controller.

Current shared control architectures, typically seen in teleoperation tasks, do not allow for dynamic sharing of control of a process. Hierarchical control algorithms are most

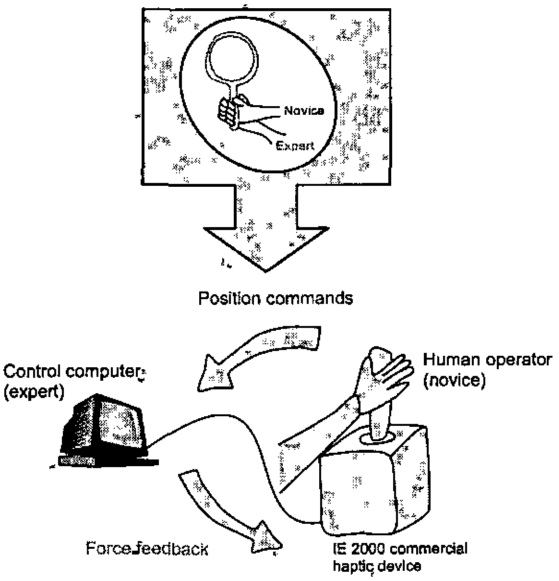

Fig. 1. Virtual Expert System: Novice human interacting with expert control system and virtual environment via shared control based on double-contact paradigm of Gillespie et al [14]

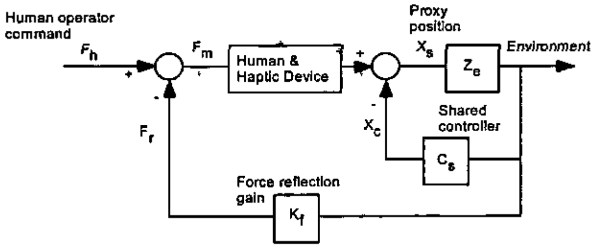

Fig. 2. Block diagram of human-robot interaction with shared control

frequently used, such that the human controls high-level decision-making and the robot controls low level systems such as force management, navigation, and obstacle avoidance. If shared control is to be used for improving skill transfer via a haptic device, the novice must eventually acquire the ability to complete all phases of the task, and this hierarchical approach is likely not well-suited. Examples of shared control in the literature are described in the following sections.

Shared control for performance enhancement

As of late, there are a number of examples of shared control for performance enhancement in virtual environments and in teleoperation systems. Steele and Gillespie implemented shared control in a driving simulator for a path following task [26]. They were able to reduce visual demand and improve path following performance with the shared control approach. Another group used shared control to suppress the swing of a crane via haptic feedback to the operator [27]. The haptic operational assistance, as it was called, employed pager motors to notify the operator of desired motions. Haptic feedback has been used for minimally invasive surgery and training, in order to improve human performance [28]. This group employed two modes of assistance for positioning and steering assistance.

In teleoperation applications, shared control is typically handled by a partitioning approach, where the human controls high-level decision making and the robotic systems controls low-level operations, such as obstacle avoidance and force management [29-37]. This has been shown to improve performance in navigation by reducing the cognitive load on the operator.

Another example of shared control for performance enhancement is described in [38]. Here, Payandeh presents a shared control concept for a robotic surgical tool. In this system, the human user and shared controller are in direct physical communication and power exchange. The shared controller can, for example, control the maximum transmission force regardless of the input commands from the user.

Shared control for skill transfer

Nudehi et al [39] proposed a "share-control" architecture for training in a telesurgery environment. In their work, two human subjects interacted with a single slave robot. Control commands to the slave were a weighted sum of the commands from the two operators, with the weighting factors defined based on the level of expertise of the operator. There was no force feedback from the slave robot to the operator; rather, the forces of interaction depend on the "share control parameter" and the error between the two command signals. This parameter is again defined based on the experience of the operator. In the case that one operator has little or no experience, the share control parameter is set to unity, causing the commands to the slave to come only from the expert user, with large force feedback gain to the novice, so that the trainee is driven to match the motions of the expert.

Prior work by the author has motivated a more thorough study of shared control as it applies to performance enhancement and skill transfer in virtual environments. Initially, the authors found that shared control in a virtual environment improved performance of a dynamic targeting task, where subjects interacted with a sprung mass and performed a hand-eye coordination task [40]. Passive assistance in the form of penalty-based, virtual fixture type feedback, and active assistance, now termed shared control, was implemented for performance enhancement. Shared control was formulated such that user was directed to control the two degree-of-freedom haptic device to suppress swing of an unactuated degree of freedom of the virtual dynamic system. As a follow-up study, the author studied the passive assistance and shared control modes for training of the task [41]. These preliminary studies were the first to directly compare passive virtual fixtures and shared control. Given the potential implications of shared control as an improved interaction paradigm for performance enhancement and training in haptic interactions, the following sections will discuss architectures for shared controller design and implementation and requirements for shared control systems.

Shared controller architectures

Shared control can more generally be referred to as a form of collaborative control paradigm. Examples of collaboration include segmentation into sub-tasks and dividing the task hierarchically. Shared control is a specific subset of collaboration that involves simultaneous control of a common process via energy and command flow [38].

The specific taxonomy proposed here incorporates three categories of shared controller architectures: hierarchical, segmented, and concurrent.

- Hierarchical
  This architecture is based on the hierarchical shared controllers implemented in teleoperation systems. In this case, the human operator controls high-level task and motion planning, while the shared controller is used to control low-level motions. This could include tremor suppression, obstacle avoidance, or force management. For the purpose of performance enhancement, the benefits are that the human operator need not concern him/herself with the fine details of motion, but can focus on the "big picture" issues. In terms of training, this architecture assumes that the human operator has some basic knowledge of the task, since the shared controller does not play a role in large-scale motion planning.

- Segmented
  This architecture is a hybrid architecture where the contribution of the shared controller and the human are still separate in terms of the management of sub-tasks; however, the allocation of sub-tasks is not based on high-level versus low-level classifications. In this circumstance, imagine control of an unactuated system such as that presented in [38, 39]. In this work, the user was asked to control an underactuated dynamic system in order to perform a targeting task. The primary difficulty in completed the task was suppression of the off-axis swing of the unactuated mass. The shared controller implemented in the human-subject experiments was of the segmented type: the user controlled planar motion of the actuated mass in the system, and the shared controller generated a force feedback command, reflected to the operator, that suppressed the swing of the unactuated mass in the normal direction. This motion was integral to the total task and feedback from the shared controller was present throughout

the interaction. This is contrary to the hierarchical architecture, where the shared controller's contribution would be at discrete intervals based on the low-level tasks assigned to it.

- Concurrent
  This is the most general form of shared control architecture. Here, the total desired motion command is known, and the force feedback to the operator is proportional to the error between the desired motion and the operator's motion. The desired motion profiles can be recorded from expert users, or can be generated based on the desired interactions with the virtual environment. With this approach, the feedback from the shared controller is holistic. In other words, with sufficient feedback gains, the haptic device will complete the task without input from the user. This is unlike the hierarchical or segmented architectures, where the shared controller is active for only a portion of the total motion of the device.

Requirements of shared control systems

Requirements of shared control systems for skill transfer extend from the recent work of [40], who defines requirements of shared control man-machine systems for performance enhancement. Requirements include a display of the machine's perception of the human, its internal state, and its intention; an ability to adapt its behavior; capabilities for monitoring behavior of the human partner and building behavior models; and the ability to adjust the level of involvement based on the current state. Although Tahboub's system is not intended for the application of skill transfer, many of these "requirements" will apply to skill transfer shared control systems, including the ability to measure the current state of the human user and adjust participation. The feature of basing future actions on the part of the machine on current states indicates that cooperation and interaction strategies for shared control must be selected in a closed-loop manner.

Experimental Implementation of Shared Control

To evaluate the effectiveness of a shared control type of haptic assistance on training, a target-hitting task was designed. In this task, a subject interacts with a planar spring-mass system, and attempts to cause one mass to hit a changing target location. The system consists of two point masses connected by a spring and a damper in parallel, shown in Fig. 3. In the experiments, the movement of mass m_1 is completely controlled by the human via a haptic joystick, whereas the motion of mass m_2 was determined solely by the defined system dynamics. Thus, this 4-degree-of-freedom (DOF) system is an underactuated system since only two DOFs are controllable directly by the human. Such a system is well-suited for an experimental study of human performance enhancement and training with haptic assistance because the motions are sufficiently complex to control, and because reflection of force feedback generated by the interactions of the two masses connected by the spring-damper is necessary for the human to accurately control motion of the system. Therefore, we can examine the forces of interaction due to the system's inherent dynamics, and those additional forces that we overlay on the environment for assistance due to passive virtual fixtures or the shared controller.

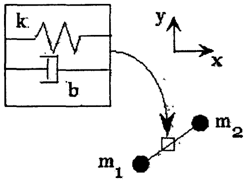

Figure 3. Virtual underactuated system. Inset shows the spring-damper model of the connection between masses m_1 and m_2.

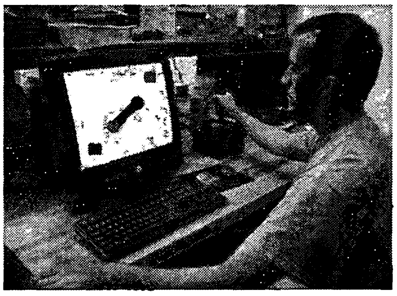

Figure 4. Subject seated at IE2000, viewing the target-hitting task.

Dynamics of the system

The dynamics of the spring-mass system in our study can be described by the following equations of motion:

$$m_1\ddot{x}_1 - F_{kx} = F_x \tag{1}$$

$$m_1\ddot{y}_1 - F_{ky} = F_y \tag{2}$$

$$m_2\ddot{x}_2 + F_{kx} = 0 \tag{3}$$

$$m_2\ddot{y}_2 + F_{ky} = 0 \tag{4}$$

where x_1, y_1, x_2, and y_2 are the x and y positions of masses m_1 and m_2 respectively. F_{kx} and F_{ky} denote the x and y components of the forces arising from the spring and the damper; and F_x and F_y are the external forces exerted on the mass m_1 through actuators on the haptic device.

Task

A target-hitting task was used to study human control of the underactuated system. Subjects viewed the virtual environment on a computer monitor and were asked to control the motion of mass m_1 via a 2-DOF haptic joystick, thus indirectly, through the system dynamics, control mass m_2 to alternately hit a fixed pair of targets. The active target was displayed in green, the other in red. After m_2 contacts the active target, the targets change color to indicate that the opposite target is then active. Fig. 4 shows a subject sitting in front of the haptic interface system with the virtual environment displayed on the monitor.

Figure 5 illustrates the four target pairs that were utilized in the experiments. They are referred to as follows: Positive Slope Near (PN), Positive Slope Far (PF), Negative Slope Near (NN), and Negative Slope Far (NF). The target pair was aligned along the line $y = x$ (positive slope) or along the line $y = -x$ (negative slope). These orientations were selected because

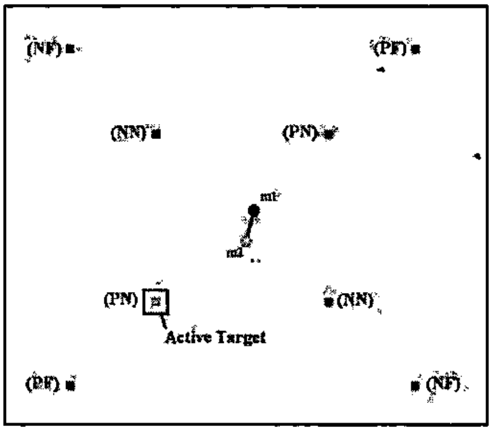

Figure 5. Graphical display of tapping experiment. Subjects control location of m_1 in order to cause m_2 to hit the desired target. Targets appear in pairs, (NF: negative slope, far; NN: negative slope, near; PF: positive slope, far; PN: positive slope, near) and the active target is indicated in green.

previous studies indicated that there was a significant difference in performance of the task with horizontal and vertical target orientations [35]. Each of the targets in a pair was equidistant from the origin. Therefore, the subjects needed to move the joystick (coupled to the location of m_1) rhythmically, either along the positive or negative sloped paths, to cause m_2 to alternately hit the target pair. Performance of the task was measured by time between target hits.

HAPTIC ASSISTANCE MODES

The goal of the experiments was to investigate the efficacy of different haptic assistance modes for training for the task described in the previous section. Specifically, the authors sought to determine if the proposed shared control paradigm was more effective than overlaid perceptual cues such as virtual fixtures for speeding up the learning process. Virtual fixtures, commonly used for performance enhancement in teleoperator systems, were implemented as a passive type of haptic assistance. The novel shared control paradigm for haptic assistance represents active intervention, since the haptic device displays forces to the user that are independent of the system dynamics of the virtual 4-DOF system and motion input from the user. The assistance modes are described in the following section.

No assistance

As evident from the name, this mode served as the control set and no haptic assistance was provided. In this interaction mode, subjects directly controlled the motion of m_1 and felt forces via the haptic device according to the dynamic equations of motion (1) through (4). F_x and F_y are due entirely to the forces that arise from the user's control of the motion of m_1 via the joystick, and the resultant dynamics due to the spring and damper system between m_1 and m_2.

Virtual fixture assistance

In the virtual fixture assistance mode, a pair of virtual walls, modeled as a spring and damper in parallel, applies forces on the subject's hand in case of deviation from the desired motion of mass m_1. For instance, if the target pair is aligned with the horizontal x-axis, then motion of the joystick, which controls the motion of m_1, in the positive y-direction will result in a force applied to the joystick in the negative y-direction. In this assistance mode, virtual walls were used to encourage users in a passive manner to move mass m_1 along the axis between targets, under the assumption that such motion of m_1 would tend to cause m_2 to move generally along the same path. The virtual wall generated forces proportional to the error in position of mass m_1, measured in the direction normal to the axis of the target pair, and proportional to the velocity of m_1 in the normal direction. These forces were subsequently displayed to the user via the 2-DOF haptic joystick. The virtual wall parameters were chosen to be $k_{wall} = 22.8$ N/m and $b_{wall} = 0.57$ Ns/m. The magnitude of F_y is due to contributions from the spring-mass-damper system forces (F_{ky}) and due to the virtual fixture feedback (F_{py}). Since the target pair for this trial is aligned horizontally, motion in the y-direction off of this axis leads to force feedback from the virtual fixture. This is the primary component of F_y, the total y-axis force displayed with the haptic device.

Shared control assistance

In the shared control assistance mode, the motion of m_2, instead of m_1 as in the virtual fixture assistance, is constrained along the desired path (the path between the two targets) to suppress the angular swing of mass m_2 due to the underactuated nature of this dynamic task.

A simple feedback controller can be implemented for position control of mass m_2 without explicitly deriving F_{kx} and F_{ky} in equations (1) to (4). Similar to the approach proposed in [37], the desired second order dynamics for m_2 can be defined as:

$$\ddot{x}_2 + \lambda^2 x_2 + 2\lambda \dot{x}_2 = -K_p(x_2 - x_d) - K_v \dot{x}_2 \tag{5}$$

$$\ddot{y}_2 + \lambda^2 y_2 + 2\lambda \dot{y}_2 = -K_p(y_2 - y_d) - K_v \dot{y}_2 \tag{6}$$

where (x_d, y_d) is the desired equilibrium point of m_2 and K_p and K_v are control gains. F_x and F_y can be solved by eliminating $\ddot{x}_2$ and $\ddot{y}_2$ from the set of equations (5) and (6) using Equations (1) through (4), as shown in Equation (7) and (8):

$$\begin{aligned} F_x &= m_1\ddot{x}_1 - m_2(2\lambda\dot{x}_2 + \lambda^2 x_2) \\ &\quad - m_2K_p(x_2 - x_d) - m_2K_v\dot{x}_2 \end{aligned} \tag{7}$$

$$\begin{aligned} F_y &= m_1\ddot{y}_1 - m_2(2\lambda\dot{y}_2 + \lambda^2 y_2) \\ &\quad - m_2K_p(y_2 - y_d) - m_2K_v\dot{y}_2 \end{aligned} \tag{8}$$

The inertia term corresponding to the inertia of mass m_1 (the joystick in this case) was considered negligible, due to the high backdrivability of the joystick. The parameter set used for the shared control assistance mode is: $\lambda = 1$, $k_p = 70$, and $k_v = 1$.

Equations (7) and (8) represent the proposed shared control methodology. This approach to shared control is unique in that it is nonhierarchical, since the forces displayed to the joystick include the system dynamics of the virtual two mass system, and the output of the automatic controller which is acting to suppress the off-axis swing of m_2. As mentioned before and verified by equations (7) and (8), these assistance forces are intended and able to suppress the swing of m_2. F_x and F_y are the total forces displayed to the user. F_{ky} is the force due to excitation of the spring-mass-damper system, while F_{sy} is the force due to the shared controller. F_{sy} is calculated such that the *y*-axis motion of m_2 is suppressed.

It should be emphasized that both the virtual fixture and shared control assistance modes only affect the motion of the system in the direction perpendicular to the orientation of the active target pair. If the joystick is released by the user, the handle will move such that the motion of either m_1 or m_2 is constrained in this perpendicular direction. However, the control algorithms will not cause m_2 to be drawn towards the active target. Therefore, the subject is required to initiate the corner-to-corner motion of the joystick necessary to cause successful performance of the task. This follows the segmented shared control architecture presented earlier in the paper.

EXPERIMENT DETAILS

Hardware

An Impulse Engine 2000 joystick from Immersion Inc., visible in Figure 4, was used to provide a high fidelity haptic simulation of the two mass system. The Impulse Engine has two degrees-of-freedom and a workspace of 6" x 6". The device exhibits low backdrive friction (< 0.14N) and a high sensor resolution (0.0008"). All simulations ran at the sampling frequency of 1 KHz. The system bandwidth for the apparatus is 120 Hz and it is capable of displaying a maximum force of 8.9N in the workspace. The virtual environment graphics were created using OpenGL.

An impedance control mode was employed in all experiments, such that user motion was measured via optical encoders on the Impulse Engine, and forces were computed according to the equations of motion of the system and the additional assistance force algorithms. It should be noted that the joystick itself served as mass m_1. The displayed forces were combinations of interaction forces between m_1 and m_2 and controller assistance forces. These forces were then scaled to improve user perception. After preliminary experiments, the values for m_2, k, and b were chosen to be 5 Kg, 100 N/m, and 3 Ns/m respectively, to ensure the system to be easily controllable.

Experiment Protocol

Fifteen subjects, four females and eleven males, participated in the experiments. Two of the subjects were left-handed, and only a few subjects had prior experience with the haptic interface or the task under study. After a practice session to orient subjects with the haptic interface device and the task, the subjects completed nine training sessions over four weeks.

A training experiment was conducted to investigate the influence of virtual fixture and shared control haptic assistance modes on human learning of the dynamic task. During the course of the training experiment, subjects were divided into three groups by assistance mode, namely no assistance, virtual fixture assistance, and shared control assistance. Subjects completed nine sessions, with each training session consisting of 40 trials (2 levels of orientation, 2 levels of distance, and 10 repetitions of presentation). In order to assess the improvement of subjects across the nine training sessions, a baseline test, in which no assistance was applied, was completed before and after each training session. For each baseline test, subjects completed 20 runs (2 levels of orientation, 2 levels of distance, and 5 repetitions of presentation), all in the no assistance mode. A training session and its corresponding two baseline tests took place in a single sitting. The nine training sessions were separated by two to three days, such that subjects completed all sessions in no less than three but no more than four weeks.

RESULTS

Training experiment results are presented in Figure 6. End-of-day baseline scores (B2) were normalized relative to the first day's B2 score. Recall that baselines scores are tabulated for subjects completing the task without any form of haptic assistance, but with feedback of the dynamics of only the mechanical system. The representation shows an interesting result. Note that in the no assistance and virtual fixture assistance modes, baseline scores oscillate around the initial score, although there is a net improvement in performance. For the group that trained with shared control for assistance, performance throughout the training sessions was always better than the initial performance level, indicating that there may be some inherent benefit to shared control for training assistance, even though statistical analysis of the baseline scores showed no significant difference. Perhaps significant differences in training effectiveness will be seen for tasks of greater difficulty. This will be a subject of future research.

An alternate representation of training results is shown in Figure 7. This figure shows the net change in performance from the end of one training session to the beginning of the next training session ($B2_i - B1_{i+1}$). All comparisons are made based on the baseline (unassisted) performance measures, and are plotted for each training group (no assistance during training, virtual fixtures during training, or shared control during training). This plot shows another interesting feature of the haptic assistance modes that is not evident in the group that merely practiced the task without assistance. As seen in the plot, the no assistance group always experiences a net gain in average inter-tap time between training sessions, except for the period between sessions 5 and 6, where performance neither degraded nor improved. For the cases of virtual fixtures and shared control for assistance during training, subjects showed a net *improvement* in performance between training sessions nearly half of the time. This fact indicates that assistance during training may have some benefits in terms of retentions. Further analysis of this phenomenon will be conducted in the future.

DISCUSSION

As a potential explanation for the trends observed in the training experiment with haptic assistance, it is possible that the shared controller, through its actions on the virtual underactuated system, is providing some information to the human user about the desired performance of the task. In other words, rather than taking over that portion of the task assigned to the automatic controller, the shared control paradigm has the effect of demonstrating desired interaction techniques to the human user on a cognitive level, therefore improving performance over long term training sessions. Along these

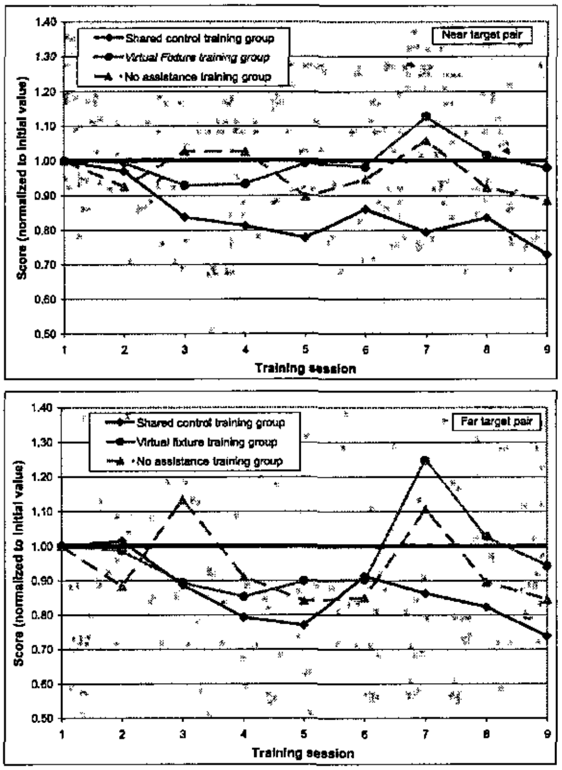

Figure 6. Normalized baseline (B2) scores for near (top) and far (bottom) target pairs for each assistance mode.

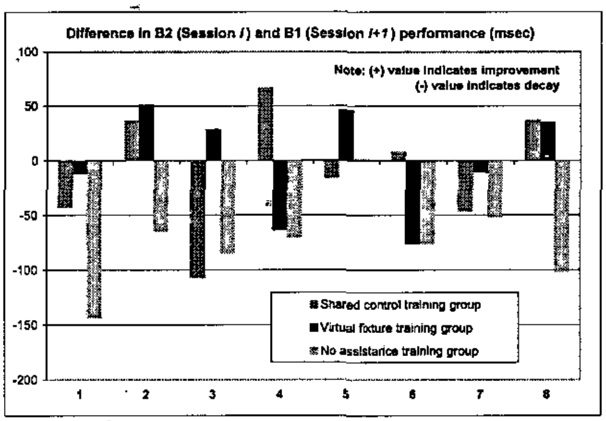

Figure 7. Regression in task performance between training sessions. Y-axis value is the B2$_i$ score minus the B1$_{i+1}$ score, where i represents the training session number. Negative values indicate that performance degraded, where positive values indicate additional improvement in task performance from one training session to the next.

lines, it could be argued that the error amplification technique that has been implemented for rehabilitation [23] has the same effect, by magnifying the undesirable consequences of interactions with the dynamic system, and demonstrating such effects to the operator. In the case of shared control, the demonstration occurs by displaying the compensatory forces to the user as part of the total force feedback command displayed via the haptic device. In the case of error amplification, the user experiences exaggerated effects of undesirable system interactions through the amplification of position error and the subsequent actions of the position controller that serves to mitigate such errors. This theory could be examined through additional experiments and analyses.

The shared control approach to haptic feedback for assistance has potential benefit for motor learning or recovery, say, following stroke, and uses errorless learning as a model for motor learning. In this way, the shared controller demonstrates desired interactions between the user and the virtual environment, encouraging the user to only interact in ways that are deemed correct. When compared to prior applications of rehabilitation robotics, including some that provide assistance, the shared control approach is novel in several ways. First, this paper reports the first study of performance improvement in a training protocol to investigate the effects of haptic assistance on performance of a dynamic task. Second, rehabilitation robotics applications that *have* employed haptic feedback have been limited to assistance in reaching tasks [19-22], with no dynamic virtual environment, or replication of rehabilitation tasks from the clinical setting, with only haptic feedback of the actual dynamics [43]. In this paper, the author proposes an alternative approach of shared control, with results shown for training of healthy subjects, as a paradigm for rehabilitation so that subjects can carry out functional tasks, and receive assistance in the form of an errorless learning approach.

CONCLUSIONS AND FUTURE WORK

This paper presents a shared control paradigm for improved training effectiveness in virtual environments with haptic feedback. Shared control is a unique form of haptic assistance in that the haptic device contributes to execution of the task via force commands from an automatic controller. Compared to haptic virtual environments that merely display the physics of the virtual system or to passive methods of haptic assistance for performance enhancement based on virtual fixtures, the shared control approach offers a method for actively demonstrating desired motions during virtual environment interactions. Specifically, the paper presents a thorough literature review motivating the use of shared control in haptic virtual environments for performance enhancement and skill transfer. Then, three architectures for shared controller implementation are proposed and described. Requirements for shared control systems are discussed as they extend to training applications. Finally, results from an experiment that implemented the segmented shared control architecture were presented, and the implications were discussed.

In the future, the proposed shared control architectures will be implemented for dynamic targeting tasks in order to assess the utility of architecture in relation to the goal of performance enhancement or skill transfer. The requirements of shared control systems, as presented here, will be implemented so that the system is able to adapt its behavior and adjust the level of involvement. Applications of particular interest to the author are training of manual tasks and rehabilitation of the upper extremity in patients suffering from stroke.

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