Haptics for Human-Machine Interaction at The Johns Hopkins University

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Abstract: The Haptic Exploration Laboratory at The Johns Hopkins University is currently exploring many problems related to haptics (force and tactile information) in human-machine systems. We divide our work into two main areas: virtual environments and robot-assisted manipulation systems. Our interest in virtual environments focuses on reality-based modeling, in which measurements of the static and dynamic properties of actual objects are taken in order to produce realistic virtual environments. Thus, we must develop methods for acquiring data from real objects and populating pre-defined models. We also seek to create systems that can provide active manipulation assistance to the operator through haptic, visual, and audio cues. These systems may be teleoperated systems, which allow human users to operate in environments that would normally be inaccessible due to hazards, distance, or scale. Alternatively, cooperative manipulation systems allow a user and a robot to share a tool, allowing the user to guide or override the robot directly if necessary. Haptics in human-machine systems can have many applications, such as undersea and space operations, training for pilots and surgeons, and manufacturing. We focus much of our work on medical applications.

Keywords: haptics, human-machine systems, virtual reality, telemanipulation, medical robotics, computer-assisted surgery

1. Introduction

The word *haptics* means "relating to or based on the sense of touch." Our research in the Haptic Exploration Laboratory at The Johns Hopkins University seeks to apply haptics to human-machine systems in order to improve performance of tasks in applications such as computer-assisted and simulated surgery, autonomous exploration of hazardous or remote environments, undersea salvage, enabling technologies, and manufacturing and design. This paper provides an overview of our recent results in two areas: realistic virtual environments and robot-assisted manipulation systems.

Section 2 of this paper considers the development of realistic haptic virtual environments. In recent years, the realism of graphical virtual environments have become quite sophisticated. Through a combination of analytical modeling and the mixed application of images of actual environments, computer-generated animation is often difficult to distinguish from the real world. In contrast, most current haptic (force and/or tactile) virtual environments are based entirely on simplified, analytical models. There is often little connection between the material properties felt in a virtual environment and the sensations received from probing real-world objects. Thus, our interest in virtual environments focuses on reality-based modeling, in which measurements of the static and dynamic properties of actual objects are taken in order to produce realistic virtual environments. Realism is crucial in virtual environments such as surgical simulators, because improper training in a simulation could result in decreased performance of actual surgeries.

Section 3 describes the use of haptics in robot-assisted manipulation systems. We consider two types of systems: telemanipulation and cooperative manipulation. Telemanipulation systems provide users with remote access to environments that are inaccessible due to hazards, distance, or scale. Such systems allow scaling of both force and position between the master and slave robots. In contrast, cooperative systems require that the robot and human operator *both* grasp the same tool. Only force scaling is allowed, since the position of the operator and robot are the same. Cooperative manipulation is advantageous in situations where the human operator desires robotic assistance, but also wishes to have direct control over the task.

2. Reality-Based Modeling for Realistic Virtual Environments

In this section, we describe our work in measuring and modeling real-world objects. We focus on several specific examples, including vibration models and tool-tissue interaction forces for minimally invasive surgery (e.g., cutting with scissors) and percutaneous therapies (e.g., needle insertion). Typically, we first design a fundamental model and then develop specialized "exploratory procedures" to populate that model with appropriate data. Then, the model is used for analysis or in a virtual environment with haptic feedback. We have developed simulators that display real-time deformation and cutting of virtual tissues. The idea of an exploratory procedure (EP) is taken from the psychology literature; humans use a specific set of EPs to explore objects.

2.1. Haptic Models for Vibration

Reality-based modeling of vibrations has been used to enhance the haptic display of virtual environments for impact events such as tapping, although the bandwidths of many haptic displays make it difficult to accurately replicate the measured vibrations. We propose modifying reality-based vibration parameters through a series of psychophysical experiments with a haptic display. We created a vibration feedback model, a decaying sinusoidal waveform, by measur-

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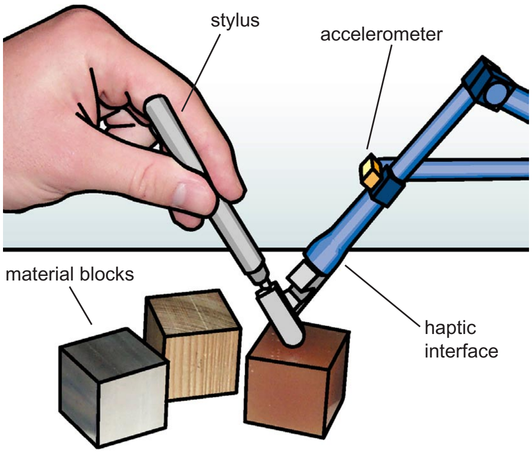


Fig. 1. Tapping on material samples (rubber, wood, and aluminum) with a stylus. The stylus is attached to the end-effector of the 3GM haptic interface, which is instrumented with an accelerometer for impact vibration measurement.

ing the acceleration of the stylus of a three degree-of-freedom haptic display as a human user tapped it on several real materials, including rubber, wood and aluminum (Figure 1). For some materials, the measured parameters (amplitude, frequency and decay rate) were greater than the bandwidth of a typical high-end haptic display (several kHz); therefore, a haptic device is not capable of actively displaying all of the vibration models. A series of psychophysical experiments, where human users rated the realism of various parameter combinations, were performed to further enhance the realism of the vibration display for impact events given these limitations. The results provided different parameters than those derived strictly from acceleration data. Additional experiments verified the effectiveness of these modified model parameters by showing that users could differentiate between materials in a virtual environment. The detailed results of this project are presented in [7].

2.2. Haptic Recordings for Cutting Biological Tissues

Current simulations of biological tissues in surgical procedures are mostly, if not completely, visual in the cutting aspect. This work is motivated by the need for haptic display not only in "poking" and "pulling" surgical tasks, but also in grasping and cutting. Virtual simulations of tissue cutting, when carefully constructed based on real data, will likely be more realistic than cadaver tissues, which have significantly different mechanical properties from living tissues. These simulations will also be more practical than physical phantoms, which cannot be reused. In addition, once the cutting data has been collected, the need to sacrifice animals for surgical training or dissection is reduced.

Our work uses "haptic recordings" to provide feedback to the user. This method of haptic rendering differs from other reality-based models, which take into account the context of the user's motion and modifications of the virtual environment. Due to the complex material interactions that give rise to forces during the cutting of biological tissues, it is very difficult to create analytical models. Similarly, empirically based models would require a significant data acquisition effort in order to characterize the many parameters affecting cutting forces. In comparison with these rendering methods, the primary advantage of haptic recordings is their simplicity and computational efficiency (a simple lookup table can be used). However, there are certainly disadvantages due to lack of flexibility and contextual information.

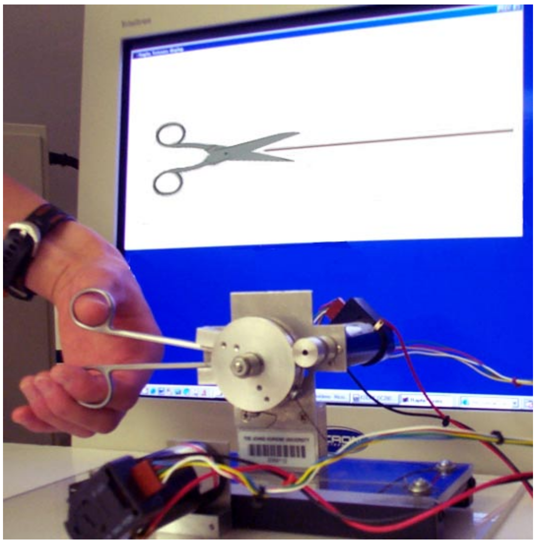


Fig. 2. The haptic scissors and graphic display. One degree of freedom of force feedback displays cutting forces between the fingers, and the other degree of freedom displays translational forces.

We have designed and tested "haptic scissors," an interface that can display forces to a user grasping Metzenbaum scissor handles (Figure 2). By filtering and scaling (but *not* modeling) cutting data from real rat tissues, we have created haptic virtual environments that can simulate the cutting of skin, liver, and tendon, as well as empty scissors. Preliminary perceptual experiments showed that the users rank the stiffness of real and virtual tissues similarly. Our work also demonstrated that users are not generally adept at identifying tissue types by haptic feedback in either real or virtual domains [4]. The use of "haptic recordings," rather than reality-based models, was simple and computationally efficient. However, the simulations lack flexibility because only the exact information obtained during data acquisition can be displayed.

Next, we tried to move beyond the "haptic recording" approach and considered two different cutting models: one based on real tissue data and one that is analytical. The model based on real tissue is a simple segmented linear empirical model of the original data. Experimental results showed that users cannot differentiate between these models and the haptic recordings created earlier [8]. The analytical model uses a combination of friction, assumed material properties, and user motion (position and velocity) to determine the displayed cutting forces, and has not yet been tested.

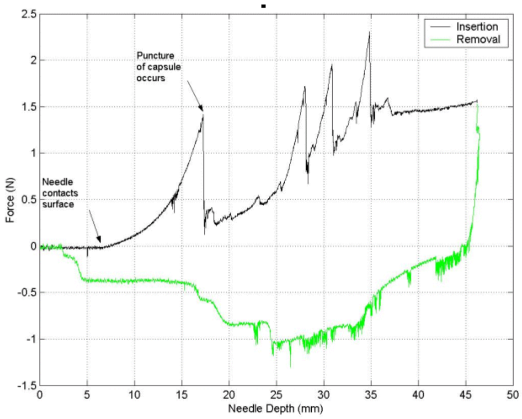


Fig. 3. Needle axial forces measured during insertion into and removal from bovine liver.

2.3. Haptic Models for Needle Insertion

The modeling of forces during needle insertion into soft tissue is important for accurate surgical simulation, preoperative planning, and intelligent robotic assistance for percutaneous therapies. We developed a force model for needle insertion and experimental procedures for acquiring data from ex-vivo tissue to populate that model. Data (Figure 3) were collected from bovine livers using a one-degree-of-freedom robot equipped with a load cell and needle attachment (Figure 4). CT imaging was used to segment the needle insertion process into phases identifying different relative velocities between the needle and tissue. The data were measured and modeled in three parts: (1) capsule stiffness, a nonlinear spring model, (2) friction, a modified Karnopp model, and (3) cutting, a constant for a given tissue [10]. In addition, we characterized the effects of needle diameter and tip type on insertion force using a silicone rubber phantom. In comparison to triangular and diamond tips, a bevel tip causes more needle bending and is more easily affected by tissue density variations. Forces for larger diameter needles are higher due to increased cutting and friction forces [9]. The models can be used to create training simulations for interventional radiologists, and to plan accurate needle placements for procedures such as prostate brachytherapy. Our future work will include the effects of needle bending, and the use of needle steering to acquire difficult targets.

3. Haptics for Robot-Assisted Manipulation

In this section, we will demonstrate the application of haptic feedback during telemanipulated and cooperatively manipulated procedures, especially robot-assisted minimally invasive surgery. We have developed studies to determine the appropriate level, sensitivity, and degrees-of-freedom required not only to create stable telemanipulation systems, but also to provide a sense of telepresence to the user. We note that haptic feedback to the operator can take the form of bilateral telemanipulation, in which haptic feedback is provided directly to the operator, or sensory substitution, in which haptic (force and tactile) data is displayed to the user through visual or audio signals. Transparency occurs when the operator feels that he or she is directly manipulating the remote environment.

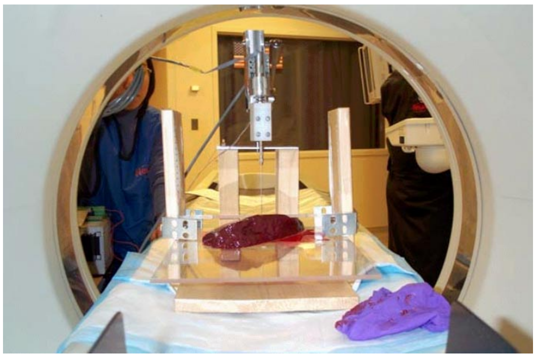


Fig. 4. Experimental setup for data collection under CT Flouro imaging. A translational stage controls the motion of the needle. The liver is suspended between two clear acrylic plates, and small holes in the plates allow the needle to pass through.

We will also illustrate the concept of Human-Machine Collaborative Systems (HMCS), which amplify or assist human physical capabilities for performing tasks that require learned skills, judgment and dexterity. Virtual fixtures in the form of anisotropic admittance have been shown to enhance the speed and accuracy of cooperative manipulation. In cooperative manipulation, both the robot and the operator hold the tool, and the system operates by admittance control. It is important to execute appropriate human factors studies to show the effect of different control laws on human operator/system performance. We provide an example of such a study for the application of virtual fixtures to a cooperative manipulation system.

3.1. The Role of Haptic Feedback in Telemanipulation

Telemanipulation is the direct human control of a robotic manipulator, where the operator and the manipulator are at different locations. It usually refers to a master/slave system, where the user operates a robotic manipulandum that is similar to the slave manipulator, and the slave emulates the behavior of the master. Telemanipulation is used in cases where the movements or forces of the user must be amplified or attenuated at the slave, and in situations where it is impractical or unsafe for a user to be at the same location as the slave.

Despite many successes with teleoperated robotic surgical systems, some surgeons feel that the lack of haptic (force or tactile) feedback is detrimental in applications requiring fine suture manipulation. We have studied the difference between applied suture forces in three knot tying exercises: hand ties, instrument ties (using needle drivers), and robot ties (using the da Vinci Surgical System from Intuitive Surgical, Inc.). Both instrument and robot-assisted ties differ from hand ties in accuracy of applied force (Figure 5). However, only the robot ties differ from hand ties in repeatability of applied force. Furthermore, comparison between attendings and residents revealed statistically significant differences in the forces used during hand ties, although attendings and residents perform similarly when comparing instrument and robot ties to

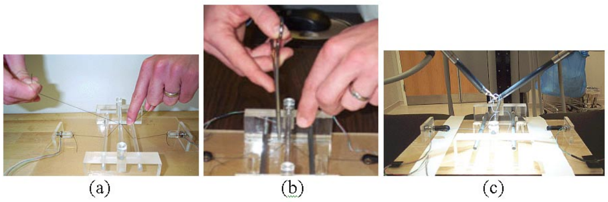

(a) (b) (c)

Fig. 5. A tension measurement device is used to measure the forces applied to sutures, (a) by hand, (b) by instrument, and (c) using the robot.

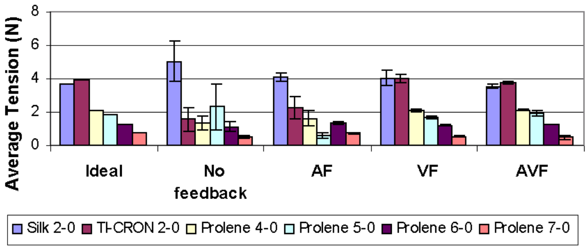


Fig. 6. Data summary for a single subject (resident surgeon, right hand). The forces applied to various sutures change with suture strength. AF = Auditory Feedback, VF = Visual Feedback, AVF = Audio and Visual Feedback. "Ideal" data comes from hand ties of attending surgeons.

hand ties. These results indicate that resolved force feedback would improve robot-assisted performance during complex surgical tasks such as knot tying with fine suture [5].

We also examined the effect of substituting direct haptic feedback with visual and auditory cues. Using the da Vinci robot from Intuitive Surgical, we observed the difference between applied forces during a knot tying procedure for four different sensory feedback substitution scenarios: no feedback, auditory feedback, visual feedback, and a combination of auditory and visual feedback. Our results indicate that the visual feedback, which gives continuous force information, would improve robot-assisted performance during complex surgical tasks such as knot tying with fine sutures (Figure 6). Discrete auditory feedback gives additional useful support to the surgeon.

Our current work studies the effect of direct haptic feedback of the performance of surgical tasks. We must determine how many degrees of freedom, what bandwidth, and what levels of force feedback must be provided, in order to both maintain system stability [?] and operator performance.

3.2. Virtual Fixtures for Telemanipulation

Current robotic systems used in applications such as robot-assisted minimally invasive surgery, undersea operation, and hazardous waste cleanup primarily attempt to convey telepresence to the operator. Recent work in our laboratory has focused on the development of cooperative and telemanipulation systems that actively assist the operator to increase the speed and precision of tasks that are remote in space and/or scale. In particular, we have studied microsurgical and minimally-invasive medical interventions. Our goal is to design "virtual fixtures" that selectively provide appropriate assistance to a surgeon, while allowing the surgeon to retain ultimate control of the procedure.

Fig. 7. Phantom haptic devices configured for teleoperation.

The term "virtual fixture" refers to a guidance mode, implemented in software, that helps a robotic manipulator perform a task by limiting its movement into restricted regions and/or influencing its movement along desired paths. Recent work at the Johns Hopkins University has shown that virtual fixtures can help a user perform precise tasks using human-machine cooperative robots (described in the following section) under admittance control [3], [6].

Admittance control with virtual fixtures, along with the stiffness and non-backdrivability of the robot, allows for the elimination of tremor and other undesirable movements away from a task path. This "steady-hand" behavior could easily be extended to master/slave teleoperators if the master and slave devices were admittance type robots, but most of the available bilateral telemanipulation literature considers only the case where the master and slave robots are of the impedance type. We have tested the interaction between various virtual fixture control laws and underlying telemanipulation control laws for impedance-type telemanipulation systems [2]. These virtual fixtures suffer from the well-known virtual wall stability problem, in which sampling rate, wall stiffness, and encoder resolution all affect stability. Our ongoing work is to develop passive virtual walls to be used as virtual fixtures on impedance control systems.

We have also developed a method for implementing guidance virtual fixtures, similar to those applied to a cooperative system, on teleoperators where the master and slave are impedance type devices. The virtual fixturing method involves controlling an impedance type robot using techniques that mimic admittance control. We implemented this method on two Phantom haptic interfaces configured for teleoperation, as shown in Figure 7. The desirable steady-hand behavior is not seen at the master (due to the physical limitations of the impedance type device), but it is seen at the slave. Implementing guidance virtual fixtures on teleoperators of the impedance rather than admittance type has the added benefit that the admittance-like behavior can simply be turned off, which allows both traditional impedance and admittance control with the same hardware. Using this method, a teleoperator of the impedance type, designed to achieve a good sense of telepresence, can also implement vir-

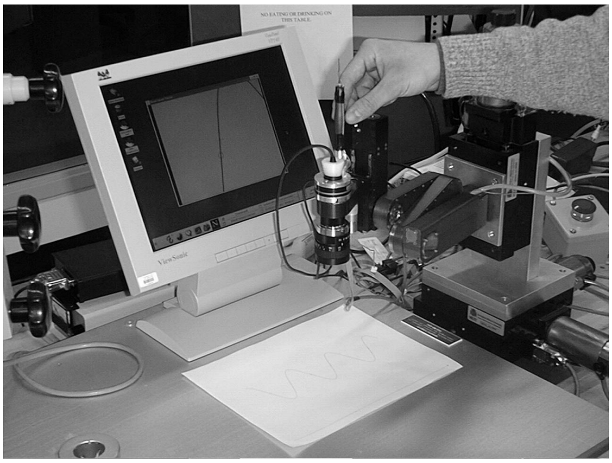


Fig. 8. The experimental setup of the Steady Hand Robot for cooperative manipulation with virtual fixtures.

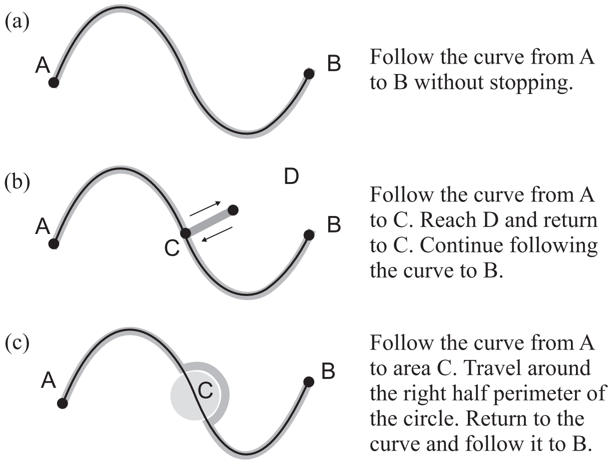
tual fixtures without the stability problems commonly associated with implementing virtual walls using impedance control techniques [1], [2].

3.3. Haptic Feedback for Cooperative Manipulation

The goal of the Human-Machine Collaborative Systems (HMCS) project is to investigate human-machine cooperative execution of small scale, tool-based manipulation activities. Our work on HMCS is specifically aimed at microsurgery. The motivation for the notion of a collaborative system is based on evidence suggesting that humans operating *in collaboration* with robotic mechanisms can take advantage of robotic speed and precision in performing such tasks, but avoid the difficulties of full autonomy by retaining the human component "in-the-loop" for essential decision making and/or physical guidance. We present two experiments with the nonbackdrivable, stiff Steady Hand Robot (Figure 8), in which the force applied by the user is multiplied by an admittance gain to create a velocity command. We examine the effects of virtual fixture guidance ranging from complete guidance (admittance ratio = 0) to no guidance (admittance ratio = 1). The admittance ratio is the ratio of the admittance gain in the direction orthogonal to the reference path to the admittance gain in the direction parallel to the reference path. Detailed results can be found in [6].

The reference path was a 0.39mm thick sine curve with a 35mm amplitude and 70mm wavelength. For Experiment II, we added a circle of radius 10mm with its center located at the midpoint of the sine curve. The subjects were provided with instructions to move along the path as quickly as possible without sacrificing accuracy, considering accuracy and speed with equal emphasis. Experiment I included 5 subjects performing the path following task three times with eleven admittance ratios from 0 to 1 (0, 0.1, . . .). Experiment II included 8 subjects performing each task three times with four discrete admittance ratios corresponding to four guidance levels (0–complete, 0.3–medium, 0.6–soft, and 1–no guidance).

At run time, the time and error a user incurred to get from Point A to Point B in Fig. 9 was recorded. The error represents the deviation from the target curve. For the off-path targeting task, the recorded time represents the time subject needed to get back on the curve after leaving it. For the avoidance task, subjects were asked to avoid the circle and no error was measured. For the data obtained in Experiment II, we performed ANOVA and multiple pair-wise comparison using Tukey's method to determine significant differences.



Follow the curve from A to B without stopping.

Follow the curve from A to C. Reach D and return to C. Continue following the curve to B.

Follow the curve from A to area C. Travel around the right half perimeter of the circle. Return to the curve and follow it to B.

Fig. 9. Task descriptions for the human performance experiments: (a) path following, (b) off-path targeting, and (c) avoidance. The black line denotes the virtual fixture reference path. The path to be followed by the user is shown in dark gray.

For Experiment I, the data indicate that improvements in error and time have linear relationships with admittance ratio, as shown in Fig. 10. This is to be expected, since the output velocity of the SHR is linearly proportional to admittance ratio.

For Experiment II, the average execution time and error were used to determine the improvement in performance with different guidance levels. For the path following task, a decrease in admittance ratio reduces error, except between medium and complete guidance. However, a decrease in admittance ratio does not improve execution time significantly. We note that none of the subjects performed worse in both time and error when admittance ratio decreased. Complete guidance resulted with the best performance but more guidance resulted in shorter time and/or higher accuracy compared to no guidance. For the targeting task, stronger guidance slowed down task execution. However, the execution times for no guidance and soft guidance do not differ significantly. The analysis also shows no difference in error for all guidance levels. In general, reducing guidance reduces the time and error during target acquisition. For the avoidance task, only the execution time was considered. The results indicate that less guidance reduces the execution time.

Overall, these results demonstrate that the selection of virtual fixture admittance is a task-dependent process. For surgical applications, error reduction is more important than time required to perform the task. For tasks that require significant interaction from the user, such as object avoidance

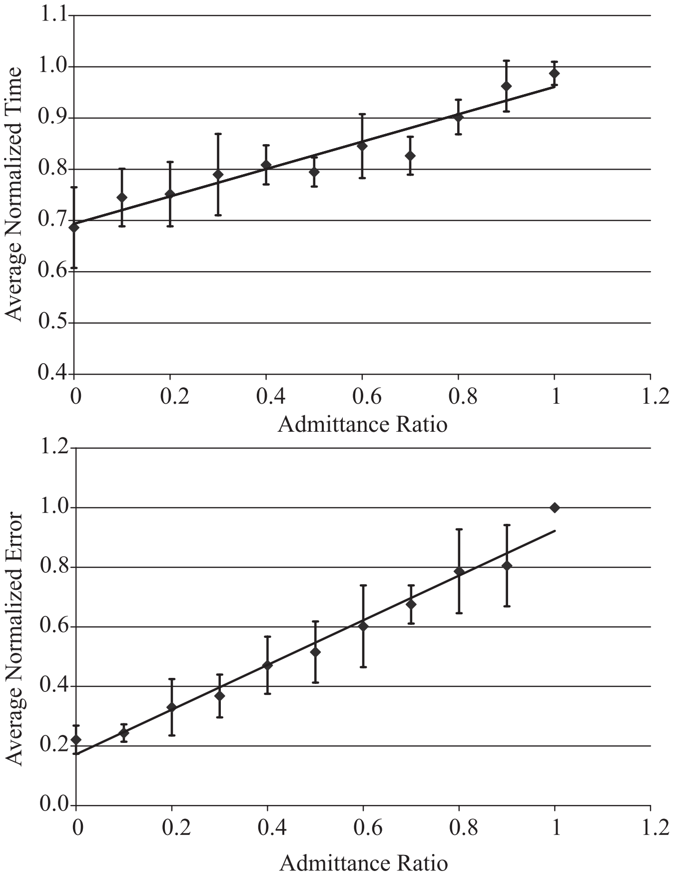


Fig. 10. Average normalized time and error versus admittance ratio for the path following task.

and off-path targeting, strong guidance will reduce accuracy and increase execution time. Therefore, lowering the amount of guidance is recommended. Based on the linear relationship between admittance and performance found in Experiment I, we developed admittance ratio selection parameters that can be used to determine an appropriate guidance level [6]. Using equal weighting for error and time, an admittance ratio of approximately 0.6 is recommended for general operation. However, admittance tuning is recommended to achieve the full benefit of virtual fixture guidance.

4. Conclusion

Our work has demonstrated the importance and potential of haptic information in human-machine systems. Virtual environments developed using realistic object models will improve training systems, particularly in the area of medical simulation. It is crucial that such simulators display realistic haptic and visual information to provide useful training for operating room procedures. In addition, teleoperated or cooperatively manipulated systems are often required because of the many tasks that cannot be accomplished with autonomous robots. Two important concepts to consider are transparency, in which the remote environment is accurately displayed to the user, and human-machine collaborative systems, in which shared control is used to actively assist the human operator. Future work will explore more complex virtual environments and human-machine systems, including more tool-tissue interaction modeling, appropriate haptic feedback, and dexterous operations.

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