

Performance Analysis of Steady-Hand Teleoperation versus Cooperative Manipulation

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Abstract

This paper compares two “steady-hand” type systems. The first is an admittance-controlled, non-backdriveable cooperative manipulation system, in which the robot and the operator simultaneously grasp and manipulate a tool. The second is a pair of haptic interfaces configured for unilateral teleoperation. A recently developed pseudo-admittance control law is applied to the master device, which attenuates the operator's high frequency input and sends a “steadied” reference position to the slave. Using a set of planar targeting tasks with varying indexes of difficulty, we found that operator movement time is similar for these two systems. However, the teleoperated system results in more targeting errors due to the limited stiffness display of the haptic interface. These results indicate that operators interact with the pseudo-admittance system as intended, but inherent physical limitations will limit applicability of this approach.

1. Introduction

Recent work in our laboratory has focused on the development of cooperative and teleoperation systems that assist the operator to increase the speed and precision

of tasks that are remote in space and/or scale. We seek to design robotic systems where the goal is not necessarily to convey telepresence, but rather to augment the remote environment with passive and active “virtual fixtures” that provide appropriate assistance. An application of particular interest is vitreoretinal microsurgery, where procedures such as retinal vein cannulation are at the limit of human motor performance [18]. Our systems will improve mechanical performance of the surgeon, while allowing the surgeon to retain ultimate control of the procedure.

We consider two types of human-robot interaction: cooperative and teleoperated manipulation. In cooperative manipulation, the robot and the human simultaneously grasp and manipulate a tool (Figure 1). The operator is directly manipulating the tool, so proprioception is maintained. An admittance control law (described in Section 2.1) and the mechanics of the device damp out operator tremor and create smooth purposeful motions. In teleoperation, a remote slave robot follows the motions of a master device, which can be a haptic interface (Figure 2). Teleoperation allows more flexibility, since position scaling and remote operation can be accomplished. Impedance control is typically used for teleoperation systems, which are often lightly damped and

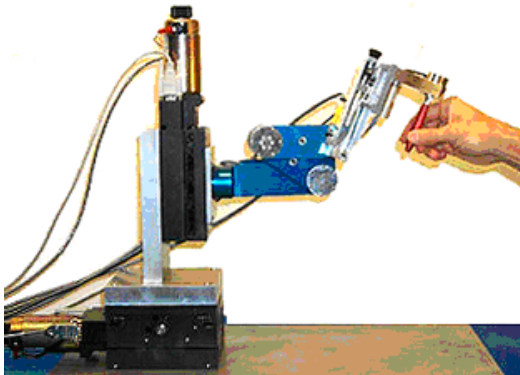


Figure 1. The Steady-Hand Robot [16], a cooperative manipulation system that operates by admittance control.

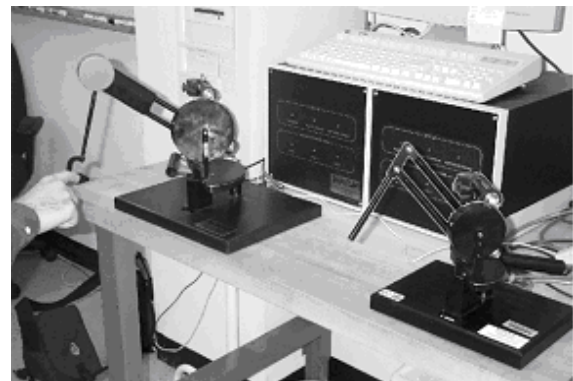


Figure 2. Two PHANTOM haptic devices [14] are configured for unilateral teleoperation, with a pseudo-admittance control applied to the master.

backdrivable.

We have implemented “virtual fixtures” on both types of systems. The term “virtual fixture” refers to a guidance mode, implemented in software, which helps a robotic manipulator perform a task by limiting its movement into restricted regions and/or influencing its movement along desired paths. Recent work has shown that virtual fixtures can help a user perform precise tasks using human-machine cooperative robots under admittance control [6,13]. We have also studied the application of virtual fixtures to impedance-controlled teleoperation systems [1,2], but the stiffness of these virtual fixtures (which are essentially haptic virtual walls) are inherently limited by stability constraints. Thus, we recently developed a pseudo-admittance control law that can be used with an impedance-type teleoperation master to provide a “steady-hand” motion as in the case of the cooperative manipulation with an admittance control law [3]. Admittance control is more suited to admittance-type robots than the impedance-type; however, the pseudo-admittance controller allows a pre-existing impedance-type system to behave like an admittance-type device. The advantage of this newly developed system is that the user can switch the pseudo-admittance controller on or off, depending on the application, to achieve admittance or impedance behavior from the same impedance-type device, which will typically exhibit less inertial and frictional effects than an admittance-type device.

This work seeks to compare the performance of the new steady-hand teleoperation method using the pseudo-admittance control law to that of a steady-hand cooperative manipulation system. Although virtual fixtures are an important motivation for this work, we are not applying them in the simple targeting task presented in the experiments herein. Rather, we want to understand the fundamental performance issues with each type of system in the “nominal” control mode (i.e., without a virtual fixture). In addition, the pseudo-admittance control on the master of the teleoperation system can be turned off, allowing operation in the “free teleoperation” mode. We compare the performance of the two steady-hand systems with free teleoperation and/or freehand manipulation. This enables us to also compare the users’ performance with and without robot assistance.

1.1. Previous Work

Admittance controlled cooperative manipulation systems have been used at the Johns Hopkins University for virtual fixtures and force scaling [5,6,13,16]. Northwestern University’s Cobots are collaborative robots that apply virtual fixtures and are implemented for large-scale tasks such as automobile assembly [15]. There has also recently been interest in admittance-type haptic interfaces [17].

Most of the available bilateral teleoperation literature considers only the case where the master and slave robots are of the impedance type [4,10,12]. There has been some research considering the case where the master and/or slave are of the admittance type [11], but achieving a sense of telepresence with this type of system is difficult because of practical limitations in how well one can cancel the inertial and frictional effects inherent in an admittance-type robot.

2. Steady-Hand Systems

2.1. Cooperative Manipulation

The Steady-Hand Robot is an admittance control system in which the velocity of the end-effector is proportional to the amount of force or torque applied by the human operator. It is explicitly designed for cooperative manipulation. The robot has 7 degrees of freedom, but only the x - y translation stages were used in the experiments. The translation stages use off-the-shelf motorized micrometer stages (New England Affiliated Technologies, Lawrence, MA) that provide a position resolution of approximately $2.5\mu\text{m}$ in both the x and y directions. The operator applies forces to the robot through a handle at the robot’s end-effector, which is equipped with a 6 degree-of-freedom force/torque sensor. The sensor has a resolution of 12.5mN.

The admittance controller relates the velocity of the robot to the force applied to the sensor by the operator.

$$\mathbf{v} = k_a \mathbf{f} \quad (1)$$

where \mathbf{v} is the desired velocity of the robot, k_a is the admittance gain, and \mathbf{f} is the force applied by the operator to the tool. This velocity is then controlled using a low-level PD controller (Motion Engineering, Inc., Raleigh, NC). The same low-level control parameters (k_p and k_d in both the x and y directions) were used throughout the experiments. Admittance control, 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.

2.2. Teleoperation

The steady-hand behavior described in the previous section could easily be extended to master/slave telemanipulators if the devices were admittance type robots. However, current teleoperated minimally invasive robotic surgical systems such as the da Vinci (Intuitive Surgical, Inc., Sunnyvale, CA) are of the impedance type [9]. Thus, our steady-hand teleoperation scheme involves controlling an impedance type robot using a technique that mimics admittance control. The method works as follows:

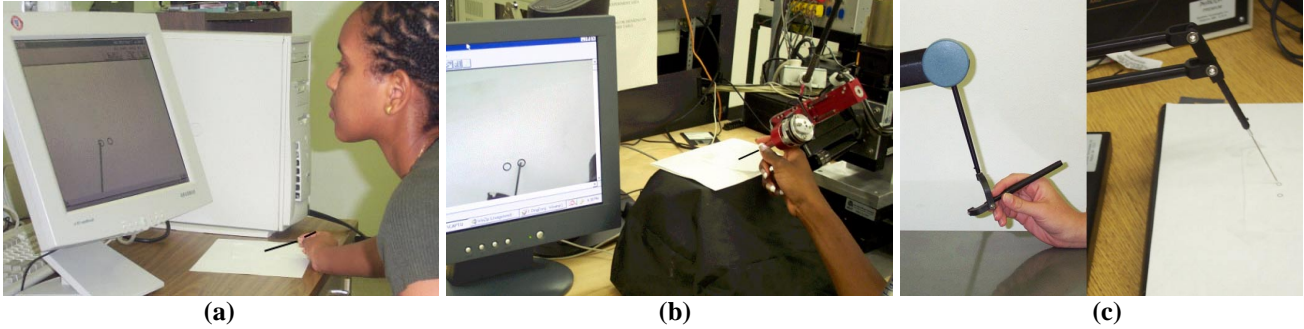


Figure 3. Conditions for the targeting experiments: (a) freehand manipulation, (b) steady-hand cooperative manipulation, and (c) steady-hand and free teleoperation.

- Regulate the master to a set point in space using traditional position servo techniques (i.e., PD control). This impedance control results in a command force, f .
- Any force applied by the operator to the master will result in a position error from the set point, and this position error can be used to approximate the applied force without the use of a force sensor.
- Use this force “measurement” to create a master reference velocity using Equation 1.
- Numerically integrate this reference velocity to generate a new set point for the master position servo loop.
- Send the set point position unilaterally to the slave robot as the position command. The slave can then use any servo technique to obtain that position.

This results in an impedance type master that feels approximately like a plant of the admittance type. Details of the control, analysis, and implementation with virtual fixtures are provided in [3].

We implemented this method on two PHANTOM haptic interfaces (SensAble Technologies, Woburn, MA) [14] configured for teleoperation, as shown in Figure 2. 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 pseudo-admittance control 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 virtual fixtures without the stability problems commonly associated with implementing virtual walls using impedance control techniques [2,8].

3. Experiments

Using a Fitts Law targeting task, we tested the performance of the teleoperation and steady-hand

cooperative manipulation systems, as well as freehand manipulation. Fitts Law states that there is a logarithmic relationship between Movement Time (MT) and the diameter and distance of target pairs [7]. This law is commonly used to test human-computer interaction systems.

3.1 Hypotheses

Consider the application of the targeting task with three different conditions: freehand, steady-hand cooperative manipulation, and teleoperation. Teleoperation can be performed with the pseudo-admittance control or in “free teleoperation” mode, where no control is applied to the master. The relationship between “free teleoperation” and pseudo-admittance controlled teleoperation is analogous to the relationship between the freehand mode and steady-hand cooperative manipulation.

Hypothesis 1: Steady-hand teleoperation and steady-hand cooperative manipulation result in the same performance, which is measured by Movement Time and error rate.

Hypothesis 2: Both of the steady-hand robotic systems improve performance over their respective freehand manipulation modes.

3.2 Experiment Design

Ten right-handed subjects, five males and five females ranging in age from 20 to 37, carried out a set of targeting tasks under three different experimental conditions. Pairs of target circles had three different diameters (1, 2 and 4 mm) and five different center-to-center distances (2, 4, 8 and 16 mm). Sets of targets that overlapped (i.e., 2 mm in diameter and 2 mm in distance) were eliminated. Therefore, there were nine different target combinations for each experiment. In all three experiments, each subject was provided with target circle pairs in random order.

Every subject was provided with a needle to act as a stylus when performing the targeting task under all conditions. Using the needle, the subject moved back and

forth between two circles printed in black on white paper. Digital video captured the two target circles and the stylus tip, which were visually displayed to the subjects on a 17-inch flat computer screen. This image was displayed to the subject, magnified by 3.43 times on a computer screen placed slightly to their left. During the tests, the subjects were only allowed to look at the computer screen.

Experiment I was a set of freehand trials (Figure 3a). Experiment II used the steady-hand cooperative manipulation system to test each combination of targets at each of three different admittance gains, k_a (Figure 3b). Experiment III used the steady-hand teleoperation system to test each combination of targets at each of three different admittance gains k_a , as well as in “free teleoperation” mode (Figure 3c).

For Experiment I, each subject was allowed to have three practice runs of 15 seconds each with the diameter set to 1, 2 and 4 mm and the distance set to 2, 4 and 8 mm respectively. For Experiments II and III, before each trial with the different admittance gains, the subject was allowed to have three practice runs with the same target trials as in Experiment I.

Each subject had 15 seconds to complete each trial and 45 seconds rest between trials. Every trial began with the prompt “Ready-Set-Go.” Upon the word “Go,” a timer was activated to count down from 15 seconds. Once time expired, the subject stopped as he/she heard a computer beep. For Experiments II and III, the subjects had 2 minutes of rest time in between the sets of different admittance gain trials.

3.3 Experiment I – Freehand

The subjects performed the nine targeting tasks freehand, equipped with a handheld needle and a wrist rest. The stylus was held at an angle of approximately 45 degrees from the target plane.

3.4 Experiment II – Cooperative Manipulation

Using the Steady-Hand Robot, subjects moved the needle between sets of target circles with varying admittance gains. For this experiment, only the x - y translation stages of the robot were used allowing motion in a horizontal plane. The movement in the z (vertical) direction was fixed so that the needle was approximately 2 mm above the targets. In addition, the end-effector was rotated so that the robot arm with the needle was approximately 45 degrees from the target plane. The needle was attached to the robot arm through a tool holder and force/torque sensor. The user held onto the tool holder. For this experiment and for Experiment III, we tested a low, medium and high admittance gain: $k_a = 5, 12.5, \text{ and } 31.25 \text{ mm/Ns}$. These admittance values are 2.5 times each other. Each of the subjects performed the

targeting task for each target scenario with the Steady-Hand Robot set with each of these admittance gains. Each subject completed a total of 27 trials.

3.5 Experiment III – Teleoperation

For teleoperation experiments, the slave robot was equipped with a needle. The subject held onto the plastic stylus of the master. The force/motion applied to the stylus in the plane of the targeting task controlled the movement of the needle. The scale of the teleoperation was 1-to-1, meaning that the master’s movement was copied by the slave with no position scaling. The PHANTOM has six degrees of freedom of position input. However, for this experiment, the endpoint of the stylus was only allowed to move in the x - y plane. The z height on the slave was fixed, using PD control, so that the needle was approximately 2 mm above the targets. The same admittance gains used for cooperative manipulation were used in this experiment ($k_a = 5, 12.5, \text{ and } 31.25 \text{ mm/Ns}$). In addition, “free teleoperation” was tested, in which there is no haptic feedback on the master, so the user can move the device freely within the x - y plane.

3.6 Data Analysis

Manual analysis of the video was used to interpret the data. From the video, the number of movements and number of errors were counted. A single movement is counted when the subject leaves a target and enters the circle of the other target. Because the subjects had 15 seconds to complete each trial, they often stopped in mid-movement when the time was finished. Thus, only complete movements were recorded, and the actual time to complete those movements was also recorded.

From this movement data, Movement Time (MT), Index of Performance (IP) and Index of Difficulty (ID) were calculated. MT measures how quickly the subject completes a single movement. The equation for MT is:

$$MT = (\text{time of trial} / \# \text{ of movements}) \quad (2)$$

A higher IP indicates better performance. The equation for IP is:

$$IP = 1 / MT (\log_2 (W/2A)) \quad (3)$$

where W is the diameter of the target circles and A is the distance between target circles. Next, the ID tells how difficult a specific task is going to be compared to other tasks. The equation for this is:

$$ID = \log_2 (2A/W) \quad (4)$$

An error is identified when a subject undershoots, overshoots, or approaches the circle from the wrong direction. The equation used to obtain percent error for each trial is:

$$\% \text{ error} = (\# \text{ of errors} / \# \text{ of movements}) * 100 \quad (5)$$

In order to analyze the data, we also averaged different values, such as MT, IP and percent error between all subjects.

4. Results

4.1 Movement Time

From the averaged results of all subjects, Index of Difficulty shows a direct relationship with Movement Time. As Index of Difficulty increases, Movement Time also increases for both the cooperative and teleoperation systems (Figures 4 and 5). Furthermore, both plots follow similar trends for the different admittance values. For example, the admittance gain of 5 mm/Ns has the slowest Movement Time with both manipulation methods. Freehand performance of these tasks had the fastest Movement Time overall. The plot for freehand manipulation was added in Figure 5 for comparison of the Movement Time between the two systems. In comparing Movement Time for the steady-hand cooperative system to that for the steady-hand teleoperation system, we found that the systems were very similar as shown for the case of the admittance gain of 5 mm/Ns in Figure 6.

4.2 Index of Performance and Percent Error

In Figure 7, the cooperative system shows a slightly higher Index of Performance over the teleoperation system for all admittance gains. The subjects performed the best in the Freehand mode, and the performance deteriorates with lower admittance gain in both systems. Note here that the Freehand mode in teleoperation refers to the “free teleoperation” whereas the Freehand mode in the cooperative system is the result of Experiment I, which in addition offers a slightly higher IP than the free teleoperation. However, the overall performance is comparable between steady-hand teleoperation and steady-hand cooperative manipulation.

On the other hand, the percent error data were not similar. The steady-hand teleoperation has significantly higher error across all admittance gains (Figure 7). Percent error for both the cooperative and teleoperation systems decreased as the admittance gain decreased. However, in comparing the percent error with Freehand targeting with cooperative manipulation, the tasks performed with an admittance gain of 31.25 mm/Ns had higher percent error than Freehand. Likewise, with the steady-hand teleoperation system, the gain of 12.5 and 31.25 mm/Ns have a higher percent error than the Freehand mode with teleoperation.

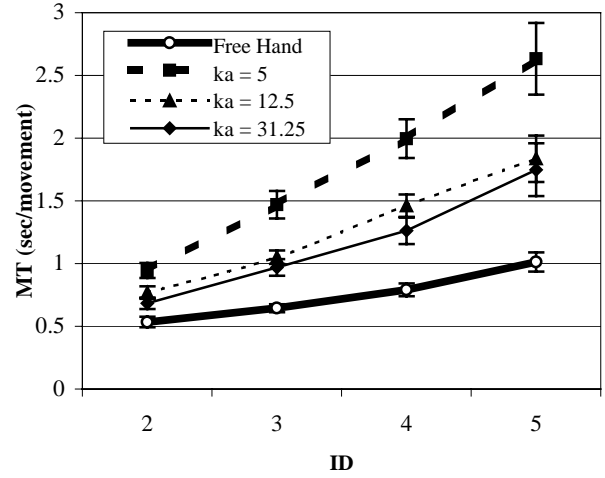


Figure 4. Cooperative manipulation Movement Time versus Index of Difficulty for different admittance gains.

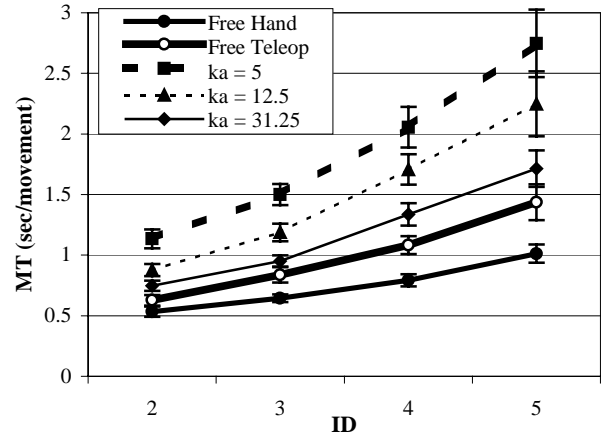


Figure 5. Teleoperation Movement Time versus Index of Difficulty for different admittance gains.

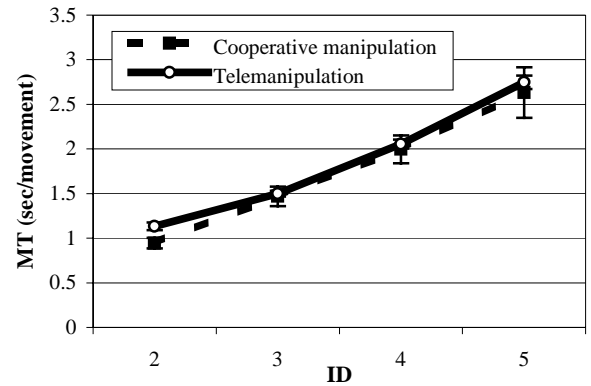


Figure 6. Movement Time versus Index of Difficulty for admittance gain $k_a = 5$ mm/Ns.

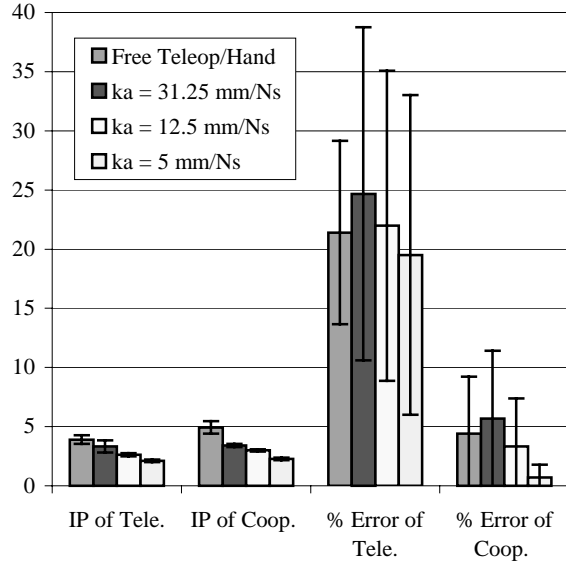


Figure 7. Comparison of Index of Performance (IP) and the percent error between different admittance gains (k_a) using steady-hand teleoperation and steady-hand cooperative manipulation.

5. Discussion

From the experimental results we can conclude that steady-hand teleoperation is comparable to steady-hand cooperative manipulation for Movement Time. However, steady-hand teleoperation has more than three times the error of steady-hand cooperative manipulation.

Some factors that may have attributed to the higher error with the steady-hand teleoperation are disorientation from the operator's loss of proprioception and inherent limitations of the steady-hand teleoperation control system. For example, the user could have been disoriented because there is some freedom (due to the limited stiffness display of the PHANTOM) to move the master robot up and down in the z -axis. However, the z -axis on the slave system was fixed, potentially confusing the operator. There is also an inherent problem with the pseudo-admittance controller. Since some significant amount of position error is needed to drive the slave, the master appears to be dragging the slave behind it. Hence the master will overshoot the target by the time the slave reaches it. Moving the master at a lower speed when approaching a target can minimize this overshoot. Another possible source of error is the phase lag introduced by a low-pass filter in the steady-hand teleoperation control system. This filter is needed to smooth the position signals obtained from encoders before they are numerically differentiated. The bandwidth of this filter was relatively high compared to purposeful human movements, so this source of error is likely to be negligible compared with the one previously discussed.

We found that both steady-hand teleoperation and steady-hand cooperative manipulation are slower in Movement Time when performing these targeting tasks than freehand. Nonetheless, steady-hand cooperative manipulation has less average percent error than freehand for all admittance values except $k_a = 31.25$ mm/Ns, as well as significantly less average percent error than teleoperation in all cases. With steady-hand teleoperation, the average percent errors of all admittance gains and for the free teleoperation mode are higher than the Freehand trials. However, the teleoperation trials with $k_a = 5$ mm/Ns have lower percent error than the "free teleoperation" mode. As the admittance gain is lowered for both systems, the percent error decreases and eventually becomes lower than performing the task in Freehand mode.

Naturally, having a robot as a medium for manipulation worsens the performance over freehand manipulation due to ergonomics, the lack of direct kinesthetic information, and the effect of the dynamics of the device. However, subjects can perform the task in a more controllable fashion as the admittance gain decreases, and at some admittance gain the advantages of using a robot outweigh the disadvantages.

6. Conclusion

We directly compared the performance of steady-hand cooperative and teleoperation systems. The experimental results satisfies our first hypothesis that steady-hand teleoperation with the pseudo-admittance control law is comparable to steady-hand cooperative manipulation in performing targeting tasks when performance is judged by Movement Time. However, the new teleoperation system results in a greater percent error when performing these targeting tasks. As for the second hypothesis stating that both of the steady-hand robotic systems improve performance over their respective freehand manipulations mode, the cooperative system improves performance by reducing the error over the freehand manipulation only at low admittance gains and over the "free teleoperation" at all admittance gains. The steady-hand teleoperation system provides improved performance over the "free teleoperation" only at low admittance gains.

It should be noted that the performance of the steady-hand teleoperation system is directly related to the bandwidth of the position servo loop that can be stably implemented on the master robot. If a master with more physical damping than the PHANTOM was used, the bandwidth of the servo loop could be increased which would likely result in lower percent error. This may result in a system that is as good as a cooperative system.

In the future, the performance of the two systems will be tested with the implementation of virtual fixtures that provide guidance to the operator. A variety of tasks will also be tested to validate which robotic system is more

beneficial when performing different tasks or complicated surgical procedures.

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