Steady-Hand Teleoperation with Virtual Fixtures

Jake J. Abbott[1], Gregory D. Hager[2], and Allison M. Okamura[1]
[1]Department of Mechanical Engineering
[2]Department of Computer Science
The Johns Hopkins University
Baltimore, MD, 21218, United States
E-mail: jake.abbott@jhu.edu

Abstract

We present a method for implementing "steady-hand control" on teleoperators where the master device is of the impedance type. Typical steady-hand systems are admittance controlled cooperative robots that can implement very high damping. Such systems are ideal for implementing guidance virtual fixtures, which are constraints in software that assist a user in moving a tool along preferred paths. Our steady-hand teleoperation method implements a type of admittance control law on an impedance-type master, but requires no force sensor. Combined with guidance virtual fixtures, the system results in a slave device that is precisely constrained to preferred paths. Experimental results demonstrate the desirable behavior of the system. This research is applicable to impedance-type telemanipulation systems, particularly those used in robot-assisted minimally invasive surgery.

1 Introduction

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. In addition, 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.

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 under admittance control [3]. In these cooperative systems, the user and the robot share the tool. Admittance control is implemented by measuring the force applied to the tool by the operator, and controlling the robot to move with a corresponding velocity.

Admittance control with virtual fixtures, along with the stiffness and non-backdriveability 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 [7, 9]. There has been some research considering the case where the master and/or slave are of the admittance type [8], 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.

In this paper, we present a method for implementing guidance virtual fixtures, similar to those applied to a cooperative system in [3], 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 implement this method on a pair of Phantom haptic devices configured for teleoperation, as shown in Figure 1. 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 impedance and admit-

Figure 1: Phantom haptic devices configured for teleoperation.

Figure 2: The Johns Hopkins University Steady Hand Robot.

tance 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, 6].

1.1 Review of Robots of the Impedance and Admittance Type

An impedance-type robot is characterized by low inertia and friction, as well as being highly backdrivable. This type of robot can be considered a "force source," and is typically controlled using impedance control. Impedance controllers output actuator forces that are a function of measured robot position/velocity/acceleration. Most haptic devices are of the impedance type.

An admittance-type robot is non-backdrivable and has large inertia and friction. This type of robot can be considered a "velocity source," and is typically controlled using admittance control. An admittance controller measures an input force, and controls the position (and its time derivatives) of the robot as a function of the input force. This is typically done by implementing a high-bandwidth velocity servo loop at a low level. Most industrial robots are of the admittance type, but there has also recently been interest in admittance-type haptic devices [14].

Devices of the impedance and admittance type are governed by the same physical laws. The distinction between these devices is in how their properties compare to those of the environment. During the execution of a given task, a robot will only experience a limited range of forces between it and its environment (including a human user), and whether these forces are large or small relative to the inertial and frictional forces of the robot determines whether the robot
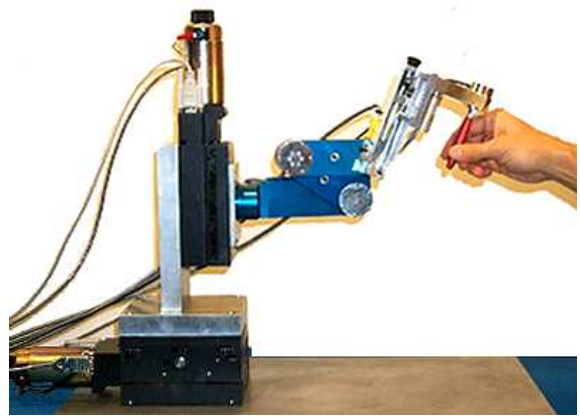
type is impedance or admittance, respectively. A good source for a comparison of robots of the impedance and admittance type is [8].

1.2 Previous Work in Virtual Fixtures

As their name implies, forbidden-region virtual fixtures [12] prohibit the motion of a robot manipulator into forbidden regions of geometric or configuration space. Forbidden-region virtual fixtures have been implemented on impedance-type teleoperators under various forms in [1, 11, 13]. It has been shown that implementing forbidden-region virtual fixtures using impedance control techniques can lead to instability [2]. This is due to the inherently nonpassive nature of virtual walls [6].

Guidance virtual fixtures guide a robot along preferred paths. In [12], guidance virtual fixtures were implemented on an impedance-type teleoperator, using potential fields (an impedance control technique). Guidance virtual fixtures have also been used in human-machine cooperative systems (where the human and robot simultaneously act on a single end-effector), such as Cobots [10] and the Johns Hopkins University Steady Hand Robot (see Figure 2) [3]. Both of these robots are of the admittance type. Unlike with potential fields, the admittance-type guidance virtual fixtures used on these devices act in a very passive way, because they do not add energy to the system.

2 Admittance Control

Admittance control typically refers to a control scheme where force is input and position/velocity is output [4]. Admittance control is generally performed on admittance type devices, but in this paper we explore a method for admittance control of impedance-type devices without the use of a force sensor.
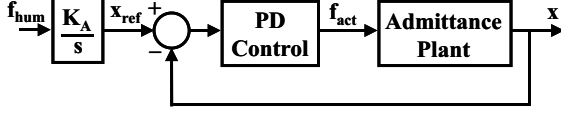
Figure 3: Admittance control of an admittance-type device requiring force sensing.

2.1 Admittance Control of Robots of the Admittance Type

Figure 3 shows how admittance control of an admittance-type device is typically conducted. A force sensor measures the force applied by the human user. This force is multiplied by a user-specified admittance gain K_A, resulting in a reference velocity

$$v_{ref} = K_A f_{hum} \qquad (1)$$

This reference velocity is integrated, giving a reference position x_{ref}, which is then given as an input to a high-bandwidth position servo loop (or v_{ref} can be given directly to a velocity servo loop). This position servo loop is typically some variation on proportional-derivative (PD) control. The result is that the robot can be commanded almost instantaneously to a desired velocity.

It should be noted that the force applied by the human is assumed to have no direct effect on the plant. The result is that the actuator force f_{act} is the only force that can move the robot. This is due to the non-backdrivability and high stiffness of the admittance-type device, and is also a simplification to model a nonlinear system as linear.

2.2 Admittance Control of Robots of the Impedance Type

In this section we present a method for admittance control of an impedance-type robot. The method works as follows:

1. Regulate to a setpoint in space using traditional position servo techniques.

2. Any applied force will result in a position error from the setpoint, and this position error can be used to approximate the applied force without the use of a force sensor.

3. Use this force "measurement" to create a reference velocity using Equation 1.

4. Numerically integrate this reference velocity to generate a new setpoint for the position servo loop.

This results in an impedance-type plant that feels approximately like a plant of the admittance type.

We will assume, for this section, that the plant can be modeled as a one degree-of-freedom (DOF) mass-damper system: $Z(s) = ms^2 + bs$. Because the plant is of the impedance type, the mass m and damping b are assumed to be relatively small. We also assume that the device is run in a quasistatic way. That is to say, inertial and damping forces are small, the force input by the user will generally be small, and the admittance gain K_A is chosen small enough that the device operates at relatively slow speeds, so that the governing equation of an impedance device

$$f_{hum} + f_{act} = Zx \qquad (2)$$

can be approximated as

$$f_{hum} + f_{act} = 0 \qquad (3)$$

Under the assumption of quasistatic operation, a constant applied force f_{hum} (and its associated constant v_{ref}) results in a constant actuator force f_{act} and velocity $v = \dot{x}$, which in turn gives a constant position error $x_{err} = x_{ref} - x$. If PD control is used in the position servo loop, a constant position error results in a constant actuator force. That is to say, during quasistatic operation, the actuator force

$$f_{act} = K_P x_{err} + K_D \dot{x}_{err} \qquad (4)$$

can be approximated closely as

$$f_{act} = K_P x_{err} \qquad (5)$$

Using Equations 3 and 5, the applied force can be measured approximately using only position information and the proportional gain of the controller.

$$f_{hum} = -K_P x_{err} \qquad (6)$$

Figure 4 shows a block diagram of how an impedance-type device is admittance controlled using the assumptions above. Since the position of the robot is typically measured with an optical encoder, differentiating the position signal for PD control will introduce noise. For this reason, the PD controller in Figure 3 is preceded by a unity-gain first-order low-pass filter with a corner frequency of ω_{LP} rad/sec, resulting in a lead controller. This does not affect the previous quasistatic assumptions considering only PD control. Figure 5 shows the actual implementation of the system in Figure 4.

Using the mass-damper plant model, the resulting transfer function from f_{hum} to v is

$$T(s) = \frac{s^2 + (\omega_{LP} + K_A K_P)s + \omega_{LP} K_A K_P}{ms^3 + \alpha s^2 + \beta s + \gamma} \qquad (7)$$
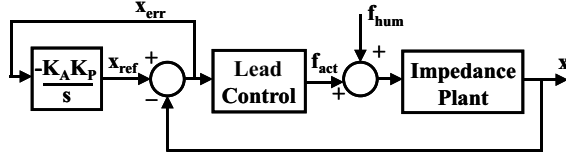
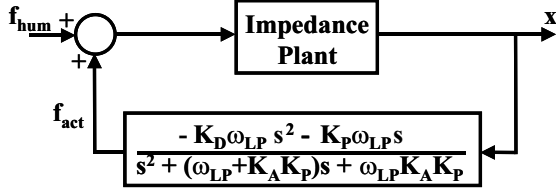Figure 4: A method for admittance control of an impedance-type device.

Figure 5: Controller implementing the concept shown in Figure 4.

where

$$\alpha = m(\omega_{LP} + K_A K_P) + b \qquad (8)$$
$$\beta = \omega_{LP}(mK_A K_P + b + K_D) + bK_A K_P \quad (9)$$
$$\gamma = \omega_{LP} K_P(bK_A + 1) \qquad (10)$$

This transfer function must be made stable by appropriate selection of gains. The filter parameter ω_{LP} must be tuned based on the encoder resolution and sampling rate of the system. It should be chosen low enough to attenuate noise, but high enough to prevent the phase lag from causing instability or noticeable time delay during voluntary human movement.

The desired velocity response to a constant force input is given in Equation 1, but the DC gain of the transfer function in Equation 7 is:

$$K_{A_b} = \frac{K_A}{bK_A + 1} \qquad (11)$$

If b is small (as it will be for an impedance-type device) and K_A is small (as it will be for admittance control), the actual admittance gain K_{A_b} felt at the device will be only slightly different than K_A. Knowledge of the plant damping b can also be used to choose K_A so that the admittance felt by the user K_{A_b} corresponds to that desired.

With admittance control of an admittance-type device, noise and bias in the force sensor typically requires the implementation of some form of deadband on the force measurement (if the magnitude of the measured force is less than some threshold, then set the measured force to zero). Otherwise, the robot will slowly drift, even when no force is being applied by the user. The same is true in admittance control of an impedance-type device. The transfer function of Equation 7 is made *asymptotically* stable by design, so the velocity can not be driven identically to zero in finite time when $f_{hum} = 0$. This results in unwanted position drift. To remedy this, a small deadband can be placed on the approximated force obtained from Equation 6, before it is used in Equation 1. An alternative solution is to add a deadman's switch, so that the reference position x_{ref} will only move if the switch is being depressed.

For the same reasons described above, gravity compensation should also be implemented. If it is not, the robot will drift down under its own weight. A gravity compensation routine will reduce the force deadband required to prevent drift.

The admittance control method presented here is capable of generating much more damping than what can be attained using traditional velocity feedback techniques. With this method, the position gain K_P is used to generate a sense of viscous damping, rather than the derivative gain K_D, which must remain small to avoid amplifying noise in the velocity signal.

3 Guidance Virtual Fixtures for Teleoperation

Guidance virtual fixtures have been studied for use with cooperative robots of the admittance type [3]. These virtual fixtures work by measuring the force applied to the robot by the user, and then implementing the admittance control method of Figure 3 only in preferred directions. Admittance control of an impedance-type device allows these same techniques to be used with impedance-type teleoperators.

3.1 Master Device

For this section, assume the master is moving in 3 DOF. Let "W" and "VF" represent the constant world frame of the robot and the user-specified virtual fixture frame, respectively. To implement guidance virtual fixtures in 3-DOF space, the cartesian position of the robot is measured in the world frame, using measurements of the joints and the forward kinematics of the device. The position error in the world frame is then used to estimate the applied force in the world frame, using the technique described in Section 2.2.

$$^{\mathbf{W}}\mathbf{f_{hum}} = -K_P {}^{\mathbf{W}}\mathbf{x_{err}} \qquad (12)$$

The applied force is then converted to the virtual fixture frame.

$$^{\mathbf{VF}}\mathbf{f_{hum}} = {}^{VF}_{W}R\, {}^{\mathbf{W}}\mathbf{f_{hum}} \qquad (13)$$

A reference velocity is now calculated in the virtual fixture frame, as described in Equation 1, using an anisotropic diagonal admittance gain matrix:

$$^{VF}K_A = diag\{K_{A_X}, K_{A_Y}, K_{A_Z}\} \quad (14)$$
$$\mathbf{^{VF}v_{ref}} = {}^{VF}K_A\mathbf{^{VF}f_{hum}} \quad (15)$$

The reference velocity is then converted back to the world frame, and used in the admittance control algorithm described in Section 2.2. Setting any of the admittance gains in $^{VF}K_A$ to zero results in no movement of the reference position in directions that are undesirable. This algorithm causes the reference position $\mathbf{x_{ref}}$ to track a desired path perfectly.

Because increasing the gains K_P and K_D eventually results in an unstable system, the impedance-type master device will not track the guidance virtual fixture path exactly, but will be bound to the path with a "virtual spring" of spring constant K_P. For this reason, K_P should be made as large as possible, while retaining stability, to improve the sense of telepresence.

Figure 6 shows a mechanical system that approximates what a user feels during quasistatic operation with this virtual fixture method. The user moves the master with mass m and damping b. The master is bound with a parallel spring-damper to a massless slider representing the reference position. The slider is constrained to move along a rail, representing the preferred path of the virtual fixture, with a damping of $1/K_A$ between the rail and the slider. This figure is an approximation because in the actual system the mass feels the effect of the damper, but the "slider" does not.

The reference position x_{ref} is not a function of x_{err}, but rather the time integral of x_{err}. This means that high frequency movements of the master are attenuated in x_{ref}. This "steadies" the reference position, even though hardware limitations limit steadiness of the actual master robot.

A constant admittance gain matrix results in guidance virtual fixtures that span entire subspaces of the virtual fixture space (planes and lines). By changing the admittance gains in real time, using computer vision as in [3], a guidance virtual fixture can help the robot follow an arbitrary path in space.

3.2 Slave Device

The control of the slave device is simple with this guidance virtual fixture method. The slave control system is a setpoint regulator that takes the reference position (rather than actual position) of the master as its input. The design of the slave's control system uses standard regulator design techniques, with sta-
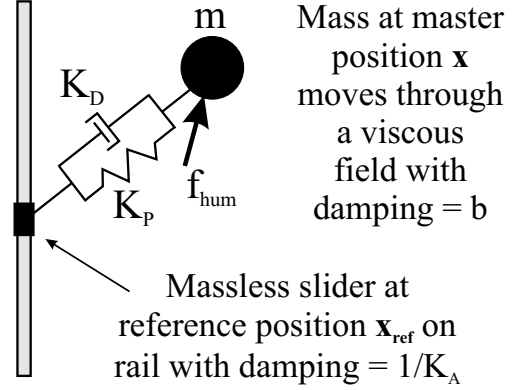

Figure 6: Equivalent mechanical system felt during quasistatic operation with guidance virtual fixtures.

bility and disturbance rejection as design goals. Because the slave tracks the "steady" x_{ref} rather than the "unsteady" x, the resulting teleoperator has desirable "steady-hand" behavior.

The virtual fixture method presented here requires an impedance-type master, but the slave may either be of the impedance or the admittance type. To achieve the benefits of switching from admittance control to traditional impedance control, an impedance-type slave will most likely be the best choice, with teleoperation with impedance-type devices being a well-understood problem. An admittance-type slave could also be used, but it would need high bandwidth, the ability to achieve velocities desired by the human operator, and a force sensor measuring the force between the slave and its environment.

Since the slave is a simple setpoint regulator with no haptic feedback to the user, it may be necessary to limit the forces applied by the slave device on its environment. If the slave is of the impedance type, this is done by limiting the force applied by the actuator (inertial and frictional forces are negligible under the previous quasistatic assumption). If the slave is of the admittance type, a force sensor is required to measure the interaction force between the slave and the environment. With an admittance-type slave, interaction force is limited by not commanding the device to any position that would tend to increase the force.

3.3 Experimental Results

We have implemented the guidance virtual fixture algorithm on a pair of Phantom haptic devices from SensAble Technologies. We used a Phantom Premium 1.5 running on a PC as the master device, and a Phantom Premium 1.0 running on a seperate PC as the slave device. The systems run independent haptic
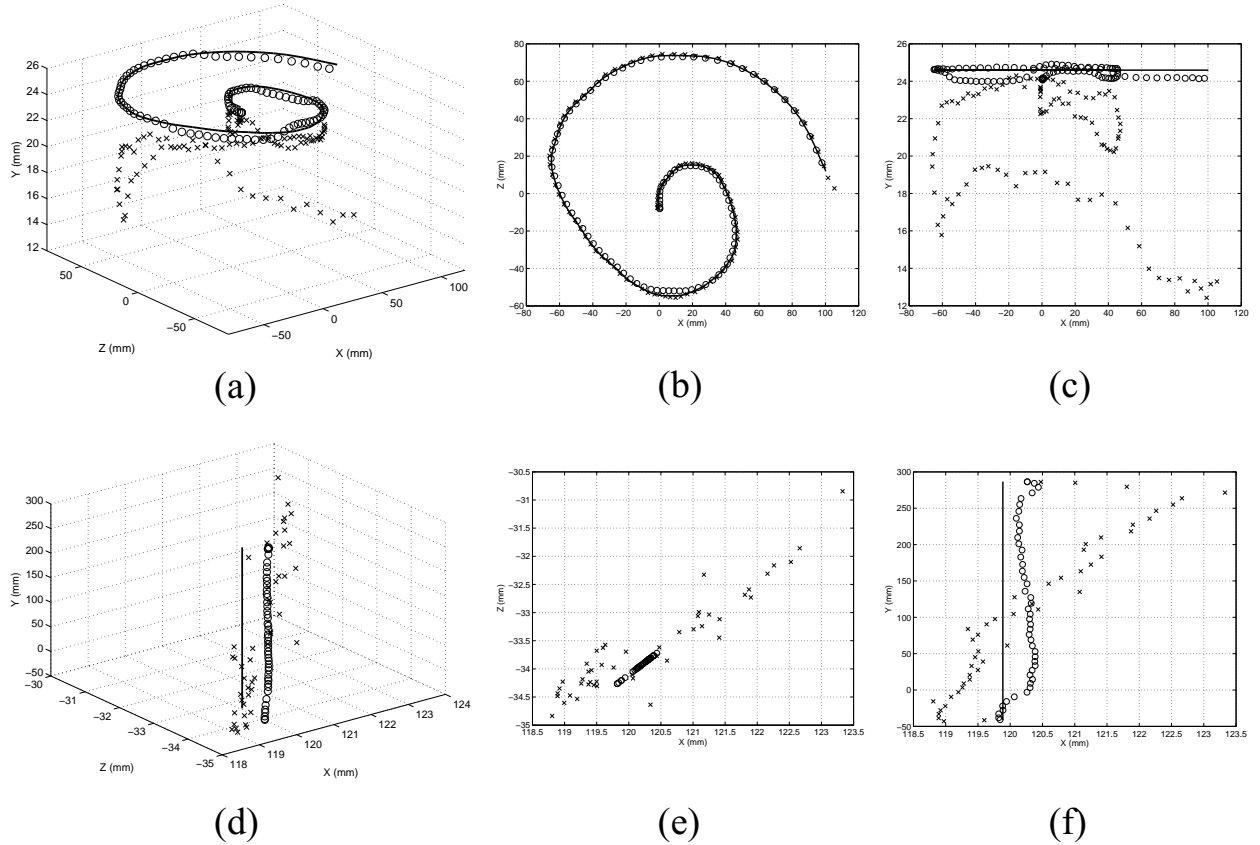
Figure 7: Experimental data. Figures (a)-(c) show steady-hand behavior in a plane, and figures (d)-(f) show steady-hand behavior in a line: ($\times$) Master position, ($-$) Reference position of master and slave, ($\circ$) Slave position.

loops at 500 Hz, and communicate over an ethernet connection with a rate of approximately 50 Hz. Because no haptic feedback is included from the slave to the master, the ethernet rate is not critical. Bilateral telemanipulation will require a dedicated communication link with a fixed sampling rate. Gravity compensation was included based on the method described in [5].

Figure 7 (a)-(c) show a guidance virtual fixture constraining the slave robot to movements in a horizontal X-Z plane. For these plots, the virtual fixture frame is aligned with the world frame $\left({}^{VF}_{W}R = I_{3\times3}\right)$, $K_{A_Y} = 0$, and $K_{A_X} = K_{A_Z} = 50\frac{mm}{Ns}$. The origins of the two frames do not coincide because the origin of the "VF" frame is set when the virtual fixture is engaged, at a location chosen by the user. Both the master and slave setpoint controllers were designed to be as stiff as possible and still remain approximately critically damped. Notice that the master can and does leave the plane (though it is attracted toward the plane), but the reference position does not. This reference position is commanded to the slave. In these plots, the user is attempting to remain in the plane, so any movement of the master out of the plane is unintentional. The master strays up to $12mm$ away from the plane, but the slave stays within $1mm$. The error between the slave and its reference position is not a function of the new method presented here, and is simply limited by the performance of the slave controller.

Figure 7 (d)-(f) show a guidance virtual fixture constraining the slave robot to movements along a vertical line. For these plots, the virtual fixture frame is again aligned with the world frame, but $K_{A_X} = K_{A_Z} = 0$ and $K_{A_Y} = 50\frac{mm}{Ns}$. The user is attempting to move in a straight vertical line, but is unable to do so. Again, the unintended movement is not present at the slave. The master strays up to $4mm$ away from the line, but the slave stays within $1mm$.

4   Discussion and Future Work

Admittance control of an impedance robot allows the guidance virtual fixturing techniques that were developed on admittance-type cooperative robots to

be applied to teleoperation systems of the impedance type. This means that these guidance virtual fixtures can be added to preexisting systems like the daVinci Surgical System from Intuitive Surgical, Inc.

It is clear from Figure 6 that K_P must be made high for the operator to retain a sense of "telepresence," but K_P is limited by stability constraints. This is an inherent limitation of our method, and thus admittance control of an impedance-type master will always result in a larger position error between the master and slave than with an admittance-type master. This loss in telepresence is proportional to operator speed, so slow and deliberate master movement mitigates this effect. With its limitations in mind, this method gives the option of implementing guidance virtual fixtures on impedance-type robots in a very passive way, without any dangerous movements that could result from using a potential field method. In addition, because there is no force sensor, the operator can move the master from any location on the device, which is not possible with robots of the admittance type.

In the future, we will add the ability of the user to move the slave away from the guidance fixture if desired, and to be gently pulled back towards the virtual fixture in a passive way, using a method similar to that described in [3]. The system presented here is a unilateral telemanipulator, so we will also investigate methods of adding haptic feedback from the slave device. This will likely take the form of the admittance gain matrix of Equation 14 changing as a function of the forces felt at the slave. In the experiment, we used an admittance gain of $50 \frac{mm}{Ns}$ because it felt obvious that the quasistatic assumption was valid. In the future we will quantify for what values of K_A the quasistatic assumption is valid. Finally, we will compare the performance of this admittance control method of impedance-type devices with admittance control of admittance-type devices.

5   Conclusion

A new method was introduced for implementing a version of admittance control of impedance-type devices. How well the device appears like an admittance-type device to a user depends on how stiff an impedance can be stably implemented. This admittance control method was used on the master device of a master/slave teleoperator to implement guidance virtual fixtures that keep the slave device on desired paths. The slave device is a simple setpoint regulator, designed to be stable with desirable damping, while achieving the best disturbance rejection possible. The proposed method was implemented using Phantom robots, and the resulting system had very desirable steady-hand characteristics.

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