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Open-Loop Bilateral Teleoperation for Stable Force Tracking

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Abstract— **Traditional bilateral teleoperation communicates both motion and force information explicitly between master and slave devices. Any such closed loop architecture trades off performance with potential instability, especially when using force measurements of high inertia slaves contacting stiff environments. More conservatively, open-loop architectures avoid stability issues, transmitting motion commands while allowing any force feedback only via sensory substitution. We propose open-loop bilateral teleoperation as an alternative communicating force information explicitly and restricting motion information to visual feedback. This naturally matches a user's needs, seeing motion and feeling forces.**

A user study was conducted to compare the novel user interface to three common open loop and bilateral control methods: position control, position control with force feedback, and rate control. The results of this study show that users are able to achieve superior force tracking with little tremor. Position tracking and trial completion time suffered from the lack of direct position connection, but training provides a promising method to restore this performance.

I. INTRODUCTION

Bilateral telerobotic systems potentially transmit both motion and force commands and measurements between both local and remote sites, sharing all information [1]. The goal is to allow a human operator to control the motion of and forces exerted by a slave robot against a remote environment. However, in practice motion tracking is usually considered the primary task, sacrificing force tracking as necessary to ensure stability.

This is particularly relevant to teleoperation systems with large slave devices. High inertia and friction forces can dominate interactions to decrease stability margins and limit force sensitivities [2], [3]. Also, stiff environments amplify small slave motions into large reflection forces that can quickly exacerbate the negative effects of hand tremor.

Avoiding any stability issues, classic open-loop architectures are more robust, transmitting only motion commands and removing any mechanical force feedback. While some sensory substitution methods can provide force information to the user [4], [5], [6], an explicit feel of the forces in unavailable.

For many telemanipulation tasks, however, we believe an inverted priority scheme better suits the user's needs. Specifically, in telerobotic applications such as space, nuclear, and deep-sea involving large slave devices making contact with stiff environments, force tracking is crucial while the

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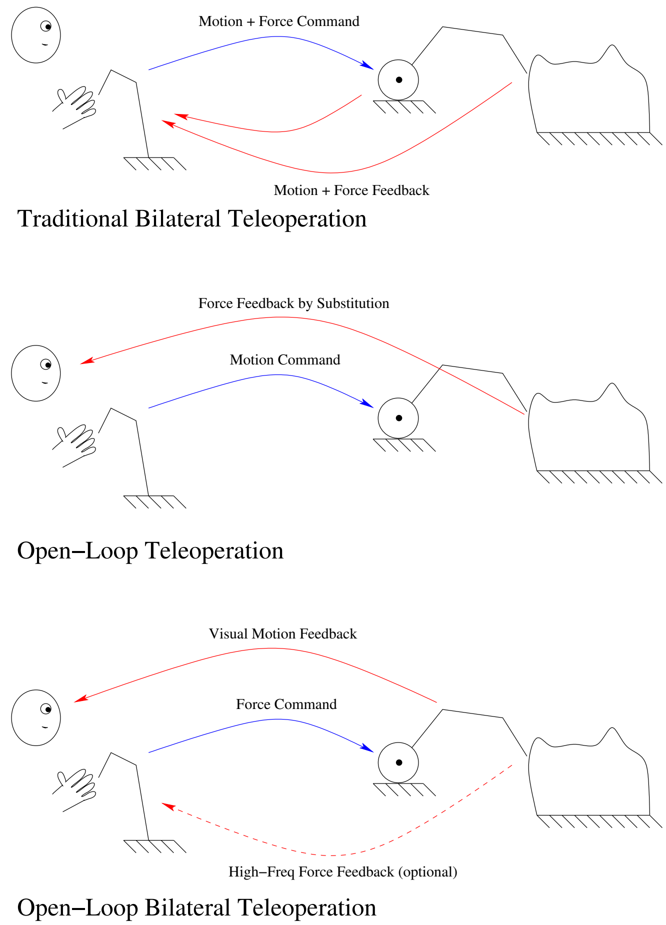

Fig. 1. Teleoperation Architectures

slave is in contact to avoid damaging the environment or slave and to complete the required task. At the same time position changes against the stiff environment surface are below any perceivable threshold and hence irrelevant to a user. Meanwhile gross movements out of contact are easily observable by visual feedback.

To this end we propose open-loop bilateral teleoperation (Fig. 1) to improve usability while guaranteeing robust stability. The user applies forces to a master device, which are sent as explicit force commands to the slave. Position feedback occurs via a visual channel, retaining the open-loop stability benefits. The slave controller implements a viscous behavior, so that motions out of contact are easily controllable by the user. The system takes on a rate-control like appearance in freespace. As such, the system enables stable motion and force control. To further enhance the user's perception of impact, high frequency slave vibrations could be presented to the user without disturbing the low frequency force tracking.

We first provide a background for bilateral teleoperation in Section II, then expound on open-loop bilateral teleoperation and its implementation in Section III. Section IV introduces and describes a user study for comparing open-loop bilateral teleoperation to other traditional teleoperation control methods. In Section V we present results and discussion of the user study, and in Section VI we offer some concluding remarks.

II. BACKGROUND

Beyond the traditional bilateral and open-loop controllers previously mentioned, several other methods have been proposed to enable stable contact with stiff environments. These architectures have primarily attempted to make the stiff environment appear softer making position control easier by using shared compliance control [7] or local force feedback [8]. Others have proposed hybrid control [9] methods employing separate types of control in freespace and in contact [10].

While positioning tasks are most naturally performed using position control [11], rate control is often used in practice (e.g. space robotics [12] and heavy hydraulic equipment) due to the mismatch of master and slave device workspaces. When the slave workspace is much larger than the master workspace, it becomes difficult to use position control. Clutching is often not intuitive and scaling up master positions into the slave workspace amplifies hand motions including hand tremor. Williams and Henry [13] presented an architecture which acts as a rate controller in free space and a force controller in contact. Mobasser and Hashtrudi-Zaad [14] proposed a method of transparent rate control and Abbott and Okamura [15] proposed a pseudo-admittance controller which can be used for rate-mode applications. It is possible to fit many of the aforementioned rate and position controllers into a general 4-channel architecture [16].

III. OPEN-LOOP BILATERAL TELEOPERATION

The general philosophy of open-loop bilateral teleoperation (Fig. 1) is to provide human operators a means of precise force tracking during contact and environment characterization during impact while maintaining position control out of contact and stability throughout all operation. This is accomplished by allowing the user to explicitly send force commands to the slave for force tracking. The user tracks slave motions through visual feedback alone. High frequency force feedback is displayed to the user haptically but is not allowed to propagate into the forward path thus preserving the open-loop nature. This approach is based on the assumption that visual feedback is available. Temporary obstructions pose little risk as potential collision forces are limited by user commands.

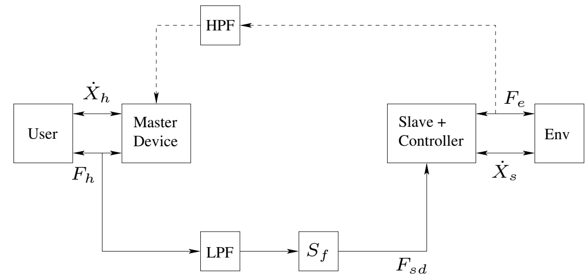

Fig. 2. General Architecture of Open-loop Bilateral Teleoperation. Low frequency force commands generated at the local site are scaled before being tracked by the slave. High frequency force measurements are optionally fed back to the user.

A. General Architecture

Fig. 2 shows a general architecture for open-loop bilateral teleoperation. A key element to this type of control is the way the controller on the slave tracks desired forces F_{sd}. While in contact, the slave can apply forces to the environment. Out of contact, however, forces are unbalanced and without control would cause continuous acceleration. Though stable, this makes motion control very difficult for the user.

To this end, the slave controller is designed to create the dynamics of a viscous damper. In contact, the additional damping helps maintain stability while forces are tracked. In freespace, a constant force command results in constant velocity, giving the system an appearance of rate control. This also allows a master device with a small workspace to control a slave across a larger workspace without excessive scaling or clutching and avoiding the amplification of hand tremor.

Open-loop bilateral control can be implemented as a non-switching controller which provides steady, consistent control throughout operation and eliminates the need for contact detection or surface normal detection. Details of the slave controller are shown in the slave side section.

While providing excellent force tracking and leveraging the benefits of rate control, open-loop bilateral control also inherits the drawbacks of rate control. In particular fine position control may feel less natural than for other systems, causing slower operation and longer task completion times. Fortunately two arguments can be made which mitigate this drawback. First, fine position control is often used as a substitute for good force tracking, in particular in stiff environments. In such situations, open-loop bilateral control may relax the need for accurate positioning. Second, humans can adapt and learn the use of rate control. For example consider the control of a computer cursor on a laptop. Many people learn and even prefer the use of a rate-controlled track point over a position-controlled track pad. Furthermore, previous tests have shown that users demonstrate exponential improvement of position and timing performance over time while using rate control [17]. Practice may be the answer to poor initial position control performance.

Additionally, measured slave forces or vibrations can be high pass filtered and presented haptically to the user.

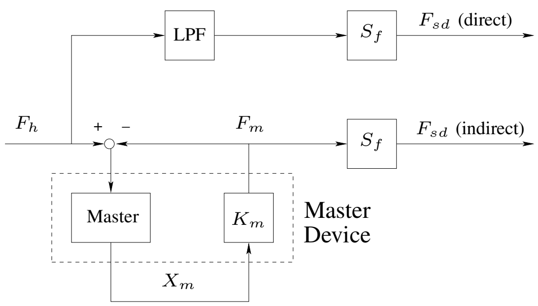

Fig. 3. Master Side Implementation of Open-Loop Bilateral Teleoperation. Forces can either be directly measured and then explicitly low-pass filtered or indirectly measured using the master structure as a low-pass filter. K_m can either be programmable or a structural part of the master device.

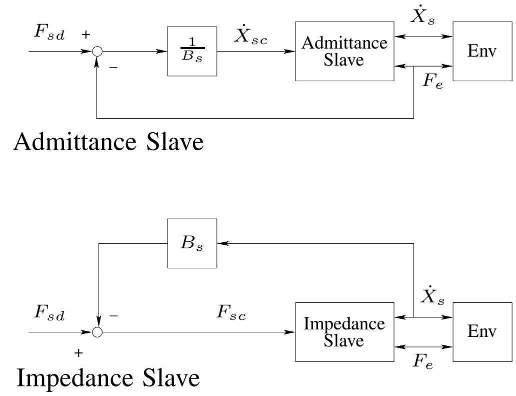

Fig. 4. Slave Side Implementation of Open-Loop Bilateral Teleoperation for an Admittance or Impedance Slave.

These high frequency forces are prevented from propagating through the forward command path by the low pass filter LPF. The cutoff frequency of the high pass filter should be set low enough to capture all of the desired impact environment frequencies. Similarly the low pass filter should be set high enough to capture all possible human motions. The cutoff frequencies of the two filters must also be separated far enough to avoid any significant overlap in order to maintain an open-loop operation state.

Open-loop bilateral teleoperation can be implemented on a variety of systems. In the following we consider master and slave requirements move specifically.

B. Master Side

The main purpose of the master device in open-loop bilateral teleoperation is to provide a means for the user to generate desired slave forces F_{sd} (Fig. 3). The master device relies on a stiffness to allow the user to apply forces. This stiffness may be structural, mechanical or created artificially via a programmed motor. One way to do this is to simply use a static load cell force sensor as the master device. As the user interacts with the load cell, forces of various magnitude and direction are directly sensed, scaled by S_f and sent to the slave. This is an example of direct measurement of desired forces. Full implementation requires an analog or digital method of explicitly low-pass filtering the measured forces. Also high-frequency haptic feedback would need to be achieved with a separate device such as a wearable tactile device.

Another way of generating desired slave forces is through indirect force measurement. In this case the master device is able to significantly deflect from a central position. The deflection is measured and multiplied by the device stiffness K_m to produce a spring force $F_{spring} = K_m X_m$. The spring force is set as the master force $F_{spring} = F_m$, scaled by S_f and sent to the slave. In this case the desired force may not need to be explicitly low-pass filtered since the master device structure acts as a low-pass filter. For example, if the master device is modeled as a mass and damper the resulting master force will be:

$$F_m = \frac{K_m}{m_m s^2 + b_m s + K_m} \cdot F_h \qquad (1)$$

This means the master device is acting as a low-pass filter with a cutoff frequency of $\sqrt{\frac{K_m}{m_m}}$. This type of device could be a joystick with a mechanical spring or it could be a freely moving device with a programmable spring. If the stiffness is programmable then the low-pass filter cutoff frequency can be set directly. It is also possible to display high-frequency haptic feedback on this type of master without the need for using a separate device.

C. Slave Side

The slave controller is required to implement viscous damper dynamics. For an admittance slave taking motion commands, we recommend an indirect force controller which converts the force error into a velocity command (Fig. 4). the force control gain is inversely related to the resultant damping and has to be tuned for stable contact with all expected environments.

For impedance slaves, the desired forces can be directly applied. The damper dynamics are most easily added as negative velocity feedback. Force measurements are not inherently necessary.

IV. USER STUDY

A user study was conducted to compare the performance of open-loop bilateral teleoperation to other stable unilateral and simple bilateral telerobotic methods.

Twelve subjects (six male, six female, all right-handed) ages 20-37 years voluntarily participated in this user study. The users were asked to track a path on an environmental surface while simultaneously applying forces to the surface. Users manipulated the slave robot through the master device by using four different control methods, which included position control, position control with force feedback, rate control, and open-loop bilateral control (see table I).

The experimental setup consisted of a Phantom 1.0 haptic master device and an AdeptOne 5-axis Scara industrial robot as an admittance slave device (Fig. 5). The master device was configured as a joystick with an effective mass of 56g and a programmable stiffness $K_m = 20\frac{N}{m}$. The stiffness was set high enough to give users adequate levels of force

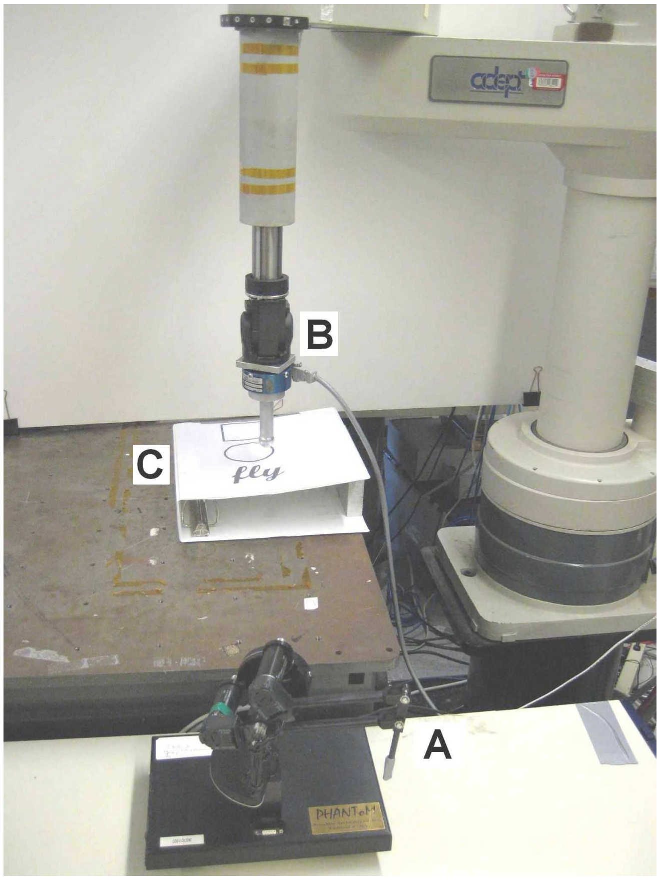

Fig. 5. Experimental Setup. A: Phantom 1.0 master device, B: AdeptOne slave device, C: Environmental surface ($K_e = 10,000\frac{N}{m}$)

feedback but low enough so as not to fatigue them after extensive testing. This resulted in an effective low pass filter at 3 Hz. The force scale $S_f = 25$ was set high enough to create reasonable rate control speeds in freespace and low enough to ensure that the user wasn't able to command damagingly large forces during contact. The slave had a tracking bandwidth of 4Hz and a system time delay of 64ms. The stiffness of the environment used for all trials was approximately 10,000 $\frac{N}{m}$ leading to deflections of up to 1cm. Through a slightly conservative analysis [3], the damping control term was set $B_s = 938\frac{Ns}{m}$ in order to maximize force tracking speed while maintaining stability.

For position control and position control with force feedback, the position scale was set to unity. The force scale for position control with force feedback had to be limited to $S_{f\_env} = 364$ to ensure stability. This is a significant decrease in force sensitivity. Users could feel the environment during operation though it felt soft and the forces were not large.

Rate control and open-loop bilateral control provided the users with a virtual spring force proportional to the distance away from the zero point. For both controllers the spring constant was set to $K_m = 20\frac{N}{m}$. For rate control the rate scale was set such that it matched the rate scale of the open-loop bilateral controller in freespace $S_{rate} = S_f \cdot \frac{1}{B_s} = \frac{25}{938}$.

Control	Command	Feedback
Position Control (**P**)	$X_{sc} = X_m$	visual only
Position Control with Force Feedback (**PF**)	$X_{sc} = X_m$	visual and $F_m = \frac{1}{S_{f\_env}} \cdot F_e$
Rate Control (**R**)	$V_{sc} = S_{rate} X_m$	visual only
Open-Loop Bilateral Control (**OLB**)	$F_{sd} = S_f F_m$	visual only

TABLE I
USER STUDY CONTROLLERS

In this way rate control and open-loop bilateral control felt identical when operated in freespace.

For user testing, each of the subjects were instructed to attempt to telerobotically trace various shapes on the environmental surface (Fig. 5) while keeping a constant contact force. The environmental surface deflected visibly while in contact giving users some additional visual sense of the amount of force being applied. The environment surface was horizontally inclined at 10 degrees so that users could not simply operate in the horizontal plane to maintain constant force while tracing but had to move up and down the incline. The shapes were designed to test different aspects of movement including curves of various arc lengths (circle and fly), sharp corners (square), and change-of-direction motions (fly).

Each user test was comprised of four sets of trials with each set being performed with a different one of the four control methods. At the beginning of each set the moderator verbally explained to the user the telerobotic control method to be utilized during subsequent trials of that set. The user was then given a couple of minutes to practice on a training environmental surface with shapes similar to the test shapes.

After practicing the practice environmental surface was replaced with the testing environmental surface. Subjects were instructed to trace the shapes on the environmental surface as closely as possible while attempting to keep a constant contact force. To prevent subjects from operating at unreasonably slow speeds, subjects were given 32 seconds to trace each shape. If they did not complete the shape in time, they had to rerun that trial. Subjects started at the top and center of the square and circle and followed the shapes around clockwise. For the fly shape, they started at the end of the 'y' and traced backwards to the beginning of the 'f'. The slave initially started in freespace, so that when the trial started the user had to first make contact and then follow each shape.

Each set of trials was complete once the subject successfully traced each shape in 32 seconds twice. The entire test was complete once the user finished the set of trials for each of the four control methods. To avoid systematic bias or learning effects when compiling and analyzing aggregate results, the order of operating each of the four control methods was randomized and varied from subject to subject.

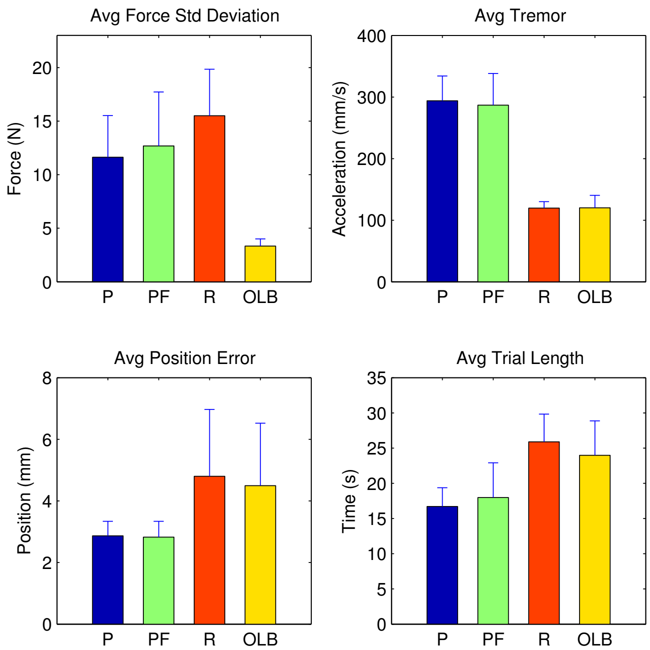

Fig. 6. Objective Results of User Study for Four Different Control Methods: **P**: Position Control, **PF**: Position Control with Force Feedback, **R**: Rate Control, and **OLB**: Open-Loop Bilateral Control

Avg Force Deviation

	PF	R	OLB
P	0.34	0.0086	1.5e-5
PF		0.18	4.7e-5
R			1.0e-6

Avg Tremor

	PF	R	OLB
P	0.44	1.2e-9	2.6e-9
PF		7.3e-8	1.6e-7
R			0.92

Avg Position Error

	PF	R	OLB
P	0.72	0.0083	0.023
PF		0.0064	0.013
R			0.68

Avg Trial Length

	PF	R	OLB
P	0.21	2.7e-6	8.5e-5
PF		3.2e-4	7.7e-4
R			0.067

TABLE II
STATISTICAL ANALYSIS OF DIFFERENT CONTROLLERS (P-VALUES)

Four metrics were used to evaluate user performance during testing. Force deviation was the standard deviation of contact forces throughout the trial. Tremor was calculated as the the magnitude of acceleration for each point throughout the trial. Position error was calculated at each point as the shortest distance to the desired trajectory. Lastly, trial length was a measure of how long it took subject to trace each shape. Force, position, and timing data was collected during trials in order to quantify these metrics. Additionally, at the end of testing, users were asked to select the control method they most preferred using and the one they least preferred using and explain their reasons behind each selection.

V. RESULTS AND DISCUSSION

Fig. 6 shows the compiled objective results of the user study. A repeating measures ANOVA was used for comparison among control methods with results given in Table II. Effectively, the force standard deviation examines the ability to apply desired forces while the other measurements examine the ability to create the desired motion. Perhaps as expected, open-loop bilateral teleoperation surpasses all other methods with respect to force tracking, while it performs equivalently to rate control for movements.

Reviewing the average force standard deviation, open-loop bilateral control shows a clear advantage in force tracking over the other three control methods as depicted in the *Avg Force Std Deviation* bar graph. Since users were asked to maintain a constant force during contact while tracing the shapes, lower force deviation demonstrated better user force control. This result matches expectations, because force tracking is being accomplished automatically by the local slave controller for open-loop bilateral control, while the other control methods rely on the user to explicitly adjust and control contact forces. Interestingly those methods with force feedback does not show an improvement in force tracking over regular position control. We believe this is due to the limited feedback gain even with the slightly compliant environment.

High tremor values correspond to more jittery, jerky slave motion and are generally a negative attribute during operation. The *Avg Tremor* bar graph demonstrates that users produce significantly less tremor while using rate control and open-loop bilateral teleoperation control. By construction, rate control and open-loop bilateral control integrate commands and add further inherent filtering compared to position control and position control with force feedback. While explicit filtering could be added to position control, this may interfere with their tracking and stability characteristics.

The average position error was a measure of position accuracy during operation. The *Avg Position Error* bar graph shows that users demonstrated significantly less position error while using position control and position control with force feedback. Again, there was no significant performance difference between rate and open-loop bilateral control or between position and position with force feedback control. The control architectures of position control and position control with force feedback are designed primarily for position tracking and perform as expected.

The final bar graph *Avg Trial Length* shows the averaged trial lengths for each of the four methods. Position control and position control with force feedback were significantly quicker than rate and open-loop bilateral control. There was no significant performance difference between rate and open-loop bilateral control or between position and position with force feedback control.

The objective results show that open-loop bilateral control offers superior force tracking and smooth operation while giving up performance in position tracking and speed of operation. Previous studies have shown that users utilizing rate control are able to demonstrate exponential improvements in position tracking and timing over longer periods of training [17]. In our study users were only given a few practice trials and the actual testing for each control method lasted only 15 minutes or less. It is possible that with more practice users may be able to use open-loop bilateral control to perform position tracking tasks as well as with using position control. However, it is unlikely that users utilizing position control would be able to show similar improvements in force tracking especially if the environmental surface was more rigid and did not provide any visible deflection to give a sense of the force levels.

The subjective results of the user study reveal that users most preferred using open-loop bilateral control or position control with force feedback over the other control methods with five subjects preferring position control, seven preferring open-loop bilateral control and none preferring the others. Subjects who preferred using position control with force feedback noted that it felt natural, was similar to operating in real life, and was like writing. Those who preferred open-loop bilateral control remarked that the operation was smooth without tremors and easy to control contact forces. It was also noted that more attention could be devoted to position control since it was relatively easy to control the force.

Subjective results also show that nine of twelve subjects chose rate control as their least preferred control method. The main reasons for choosing rate control as the least preferred method were that it was difficult to control contact forces and that position control was not intuitive. Two subjects chose position control as their least preferred method, one pointing out a dislike at not having any haptic feedback and the other not preferred the propagation of hand tremors. One subject chose position control with feedback as the least preferred method also indicating a dislike of hand tremors.

VI. CONCLUSION

In this work we have introduced open-loop bilateral teleoperation as an alternative to traditional unilateral or force-reflecting bilateral teleoperation. It focuses on force tracking as the primary explicit control objective and relies on visual feedback for position tracking. Because there is no overall closed control loop, the system is able to operate effectively in both freespace and rigid contact without stability issues or gain switching. It also allows much higher force scales than otherwise possible.

The user study confirms superior force tracking capabilities and motion tracking abilities equivalent to rate control. The study also showed users split over whether the rate-control-like user interface was liked and easy to use. To further improve the user experience, we plan to incorporate high-frequency vibration feedback and test other master devices in future work.

We believe with training and in applications requiring manipulation of stiff objects, such as satellite servicing, assembly, and nuclear cleanup, the open-loop bilateral teleoperation interface provides an effective tool with superior performance. We offer open-loop bilateral teleoperation as a means of improving general teleoperation and ultimately connecting humans to remote environments in a more useful manner.

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