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User-Controlled Variable Impedance Teleoperation

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Abstract— **Telerobotics fundamentally aims to project human skills into a remote, unstructured environment. A key component of human skills is anticipatory modulation of limb impedances in accordance with task requirements and in expectation of events or disturbances. These adjustments occur continually in human interaction strategies, yet are mostly masked in telerobotics by limited bandwidth controllers and fixed impedance hardware.**

We propose a telerobotic architecture with user-controlled variable impedance and show a single degree of freedom experimental implementation. The master incorporates a grip force sensor as an additional impedance command channel. Since grip force correlates with the user's own impedance, this input provides an intuitive and natural extension to the regular interface. On the slave, a physically variable clutch actuator is used to adjust both low and high frequency impedance. The additional command channel allows the operator to utilize impedance variation strategies to control impact forces and accomplish varying tasks. These natural interaction strategies are simpler and more robust, leading to superior performance and a telerobot which more effectively represents the operator.

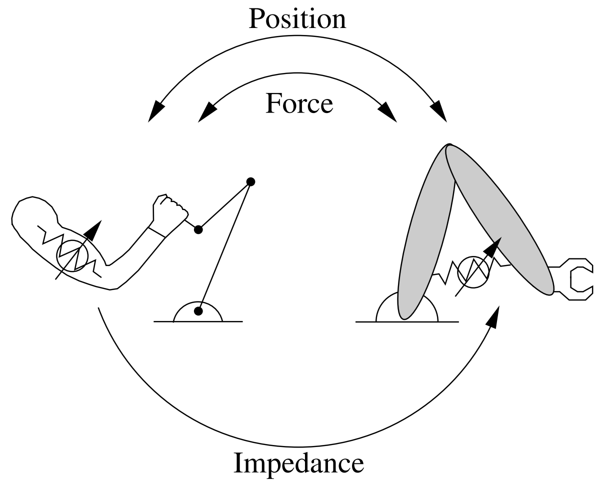

Fig. 1. User-Controlled Variable Impedance Architecture

I. Introduction

The development of telerobotic systems for use in unstructured environments remains a challenge. Due to the diverse nature and unpredictability of such environments, telemanipulators must be capable of interacting both gently and firmly to complete a wide range of potential tasks. Safe exploration necessitates compliant operation with small forces, while accurate positioning under load requires stiff operation with large forces. As task requirements vary, stiff interfaces are unable to effectively perform safe exploration, while compliant interfaces cannot accomplish accurate positioning. A reconfigurable system provides a potential solution if it can continuously adjust to the task needs.

This notion is supported by human interaction strategies. We anticipate task needs and modulate our impedance, allowing us to achieve delicate force control and stiff position control, move heavy loads, and stabilize unstable dynamics[1]. We vary our impedance by selecting appropriate limb configurations as well as co-activating antagonistic muscles[2]. We propose that an effective human-in-the-loop telerobotic system should reproduce these behaviors and vary the slave impedance. The system should leverage human intuition and skill by allowing the operator to set the slave impedance, either explicitly or by transparently sensing their impedance as they perform tasks.

The successful realization of a variable impedance telerobotic system must take into account the slave impedance at both low and high frequency. While stiffness regulation implemented in software[3], [4] is effective at modulating low frequency impedance, impact forces are dominated by the high frequency impedance. Safe exploration, then, requires a hardware variable impedance actuator based on variable mechanical couplings or other designs.

In this paper, we propose and demonstrate a telerobotic architecture that leverages a slave robot with variable impedance actuation. The user supplies the desired slave impedance in real time through an additional and intuitive 'impedance-sensing' input. Regular feedback control implements the slave impedance at low frequencies, while physical variation of the actuator impedance alters the slave impedance beyond the bandwidth of any controller. The general architecture is pictured in Figure 1.

We construct an experimental single degree of freedom (1-DOF) system utilizing a magnetorheological (MR) series clutch actuated slave and a master equipped with grip force sensing. A system characterization shows the effectiveness of slave impedance modulation, allowing safe interactions with low impact forces as well as large sustained forces. User tests then explore the utility and effect of the additional impedance command channel. The operator employs different and simpler strategies if the channel is available, leading to safer operations under productivity constraints. Effectively, the system provides a variable tool for variable tasks.

Section 2 presents the general variable impedance archi-

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tecture, while Section 3 details our 1-DOF implementation. Section 4 discusses user experiments demonstrating simpler, more intuitive task completion strategies.

II. Variable Impedance Telerobotics

Traditional telerobotic approaches have used a combination of position and force channels relaying information between the slave and master[5], [6], [7]. The benefits of allowing the operator to alter the low frequency stiffness of the slave and master via software gains has been explored previously in [8]. It is experimentally shown that altering the slave stiffness in particular improves the performance of highly variable tasks; however gains were changed discretely by push-button and there were no experiments in which the user could change stiffness in real-time.

To leverage the variable stiffness benefits both in real-time as well as over the entire frequency range, we propose two improvements. The addition of an impedance command channel will allow continual adjustments based on the user's observations or anticipation. Variable impedance actuators will enable adjustments to affect slave impacts and other high frequency events outside of the bandwidth of feedback control.

A. Variable Impedance Actuation

While low-frequency impedance control can be achieved through feedback[3], [4], the inertia of the slave device will dictate the high-frequency impedance and thus have a profound influence on the peak impact forces and safety of the device. In order to alter their high-frequency impedance, slave devices must be designed with mechanically variable couplings[9], [10], [11], [12], [13].

B. Impedance Commands and Human Impedance Sensing

To continually select the slave impedance level, a desired impedance input needs to be supplied at the master. Here we identify two options.

The first approach is to transparently measure the user's limb impedance. In a fully immersive system the operator should naturally modulate their impedance to suit the situation. By using a measurement of this impedance to control the slave impedance, the natural intuition of the user is exploited without imposing additional control requirements or training. The system sets the slave impedance without direct user attention to increase the sense of telepresence. The operator impedance can be estimated in real-time by introducing small, non-disruptive vibrations into the master[14].

If the telerobotic system is not sufficiently immersive, the user may not naturally or reliably modulate their limb impedance in response to differing tasks. In this case, we propose that an explicit impedance command should be used. The interface should be simple, predictable, and robust in order to minimize the user's required attention.

As most current telerobotic systems are not fully immersive, we propose the use of an explicit input channel. However, to minimize necessary attention and enhance the sense of telepresence, we avoid knobs or banks of switches. We use a grip force sensor integrated into the master interface. Grip force is intuitive to use and highly correlated to the user's impedance. As such, we exploit the best of both options, an intuitive interface allowing explicit commands to provide an easy to use and pragmatic tool.

C. Haptic Feedback

Historically, it is sometimes desired to hide the slave dynamics from the user. For example, hiding the slave inertia will reduce operator fatigue. As a result, haptic feedback is limited to environment interactions.

In variable impedance telerobotics however, we feel it is important to make the changing slave impedance observable through the haptic display. This increases the user's situational awareness, providing them with a sense of the remote interaction impedance in addition to the position and force signals. Thus, when the slave is at low impedance the user will feel a light and back-drivable interface that they can easily and safely move around. When the slave is at high impedance and more dangerous, the user will get a sense that they are moving a heavy tool.

III. Implementation with Variable Impedance Series Clutch Actuator

We have implemented the variable impedance telerobotic architecture in 1-DOF using a variable impedance MR clutch actuator slave device[13] and a grip force sensing master device[14].

A. Variable Impedance Slave

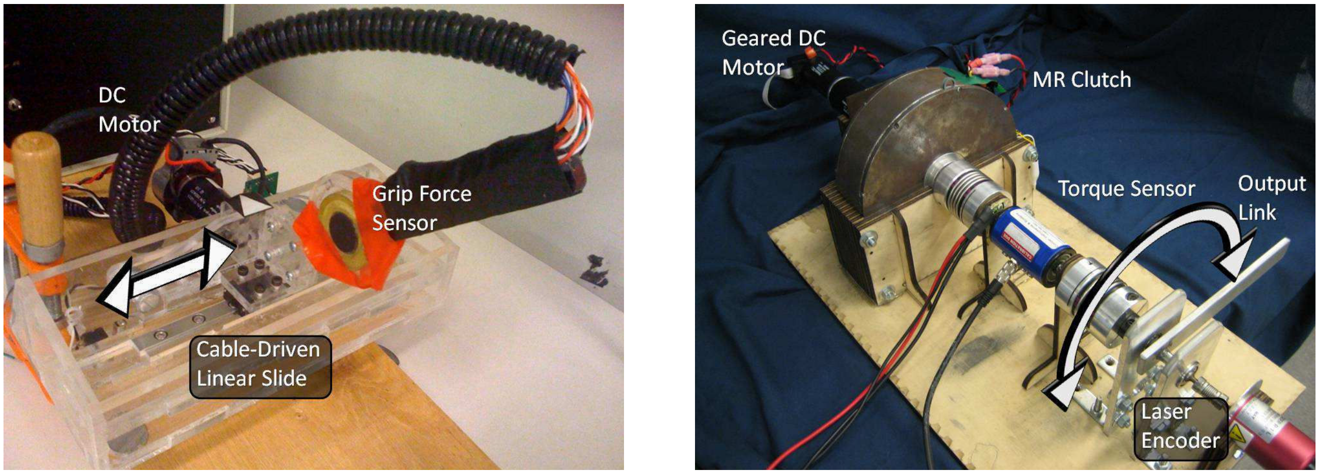
The slave device shown in Figure 2b is composed of a highly geared DC motor coupled to an output link through the MR clutch. The clutch acts by transferring torque between the DC motor and the output link up to some saturation torque, dictated by the magnetic activation experienced by the MR fluid. This acts as a non-linear decoupling device. At very high magnetic fields, large torques can be transmitted, allowing the clutch to perform as a rigid coupling. At low magnetic fields, the clutch is unable to transfer torque and the clutch decouples the output link from the reflected inertia of the motor. Since the output link has a very low inertia, the clutch is capable of nonlinearly decoupling up to 98% of the actuator inertia from the output link. This creates a large effect on the high-frequency impedance of the device, which is dominated by inertia.

A local force-feedback loop on the slave device, tuned for stable contact with the slave's environment[13], is employed to track desired forces.

This device was selected for the range of high frequency impedance it can achieve, allowing a large variation in impact forces. It should be noted that the clutch is unable to transmit large torques at low impedance, a characteristic which is also often observed in biological systems.

B. Impedance Sensing Master

The master device shown in Figure 2a is a stylus device mounted on a linear slide and cable-driven by a DC motor. Pressure sensing resistors have been installed on either side of the stylus where the user grips in a manner similar to holding a pen. These pressure sensing resistors are used to sense the forces applied on both sides of the master by the



(a) Master Device

(b) Slave Device

Fig. 2. One Degree of Freedom Variable Impedance Telerobotic System

user's grip. We average the two forces to estimate grip force. Note that previous work shows that grip force correlates with user impedance[15], so it serves as a logical input to command slave impedance.

As a consequence of setting impedance based on grip strength, application of any force by the user will raise the slave impedance. This effect is mirrored in biological actuation, where application of force via antagonistic muscle contraction necessitates a minimum impedance be created. This also mirrors the clutch's ability to transfer larger forces only at higher impedances. So while the impedance command is explicit, its effect on the slave is reinforced by the user's intuition developed through biological experiences.

C. Telerobotic Control Architecture

The control architecture implemented for the system is shown in Figure 3. A PD creates a virtual coupling between the master device and the end effector of the slave device. Forces are unscaled, while the master position is scaled up by 11.36 to match the differing workspaces. Local force feedback on the slave device ensures accurate force tracking.

The user's grip force controls the slave impedance in two distinct parts: First, it regulates the clutch activation. This activation causes mechanical changes in the slave's high frequency impedance by limiting the output force[13]. Second, the grip force scales the PD feedback gains as these determine the slave's low frequency impedance.

To facilitate haptic feedback and provide a symmetric system, these adjustments are mirrored on the master. In particular, to allow the user to experience the correct forces, the master forces are saturated to a level matching the actual slave clutch saturation level. This limit is also applied to the proportional term of the PD to provide control authority for damping large position errors.

In detail, the user's grip force is first scaled by a comfortably achievable max grip force, $F_{grip,max}$ to determine a dimensionless desired impedance level

$$\eta = \frac{F_{grip}}{F_{grip,max}} \qquad \text{with} \qquad 0 \le \eta \le 1$$

The controller gains and clutch activation are computed as

$$\begin{aligned} k_p &= k_{pmin} + \eta \cdot (k_{pmax} - k_{pmin}) \\ k_d &= k_{dmin} + \eta \cdot (k_{dmax} - k_{dmin}) \\ F_{sat} &= F_{min} + \eta \cdot (F_{max} - F_{min}) \end{aligned}$$

$$\begin{aligned} &k_{pmin} = 0.0675\ N/mm &&k_{pmax} = 1.5\ N/mm \\ &k_{dmin} = 0.000375\ Ns/mm &&k_{dmax} = 0.0225\ Ns/mm \\ &F_{min} = 0.65\ N &&F_{max} = 40\ N \end{aligned}$$

Stability of this variable gain, nonlinear system is difficult to analyze in general. The additional input η creates a new feedback path, which may allow the system state to affect the system gains. However, we note that for a two-finger grip, changes in system state will shift forces between the opposing fingers. The grip force F_{grip} and input η will remain approximately constant. Therefore, without voluntary user input, the system resembles a stable, fixed gain impedance controller.

D. System Characterization

With the system implemented, several tests were run to characterize its properties.

Figure 4 shows the peak impact force generated by collisions between the slave and a hard surface at different velocities for several η values as well as with the clutch replaced with a rigid shaft. At full activation the clutch behaves like the rigid link until saturating. Lower activations saturate at lower forces as well as attenuate contact forces at lower velocities. The minimum activation allows very little torque transfer from the motor. These characteristics allow the user to control the magnitude of impact forces.

The control architecture saturates the master force and scales the PD gains with impedance, giving the user a sense of the slave impedance and effective inertia they are controlling in the remote environment. This is described by Figure 5, where a 2 N force applied to the master device results in different motions for high and low impedance. In the low impedance case, the master device accelerates rapidly.

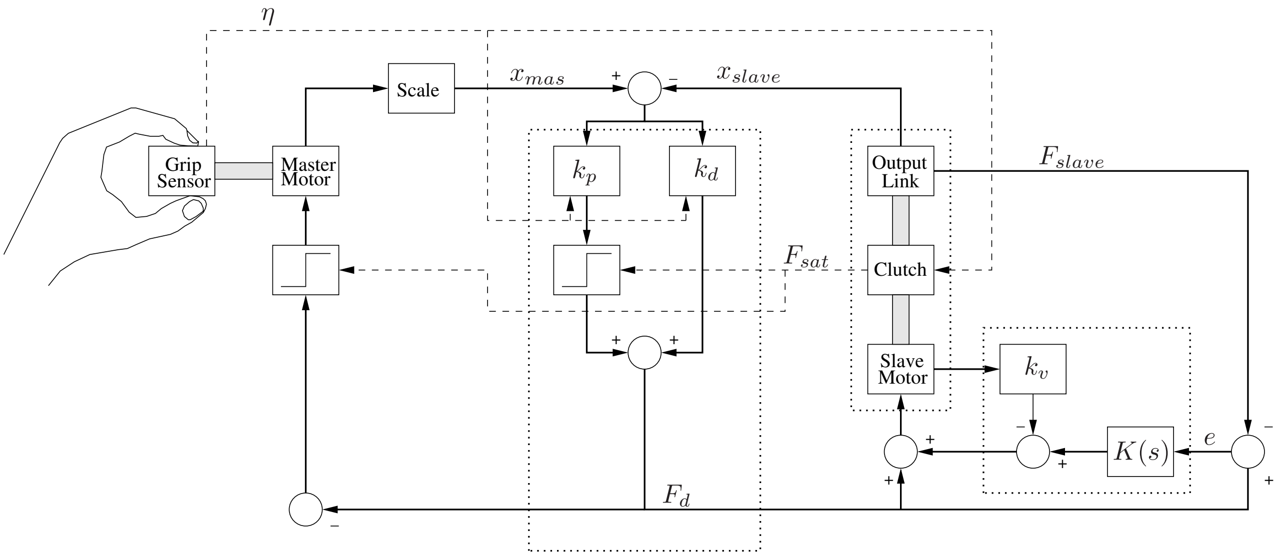


Fig. 3. Variable Impedance Control Architecture

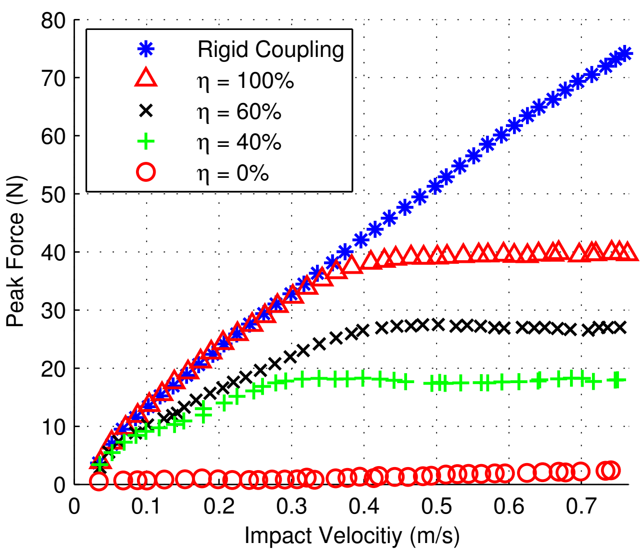


Fig. 4. Impact forces as a function of impedance level, η (0-100%), and impact velocity

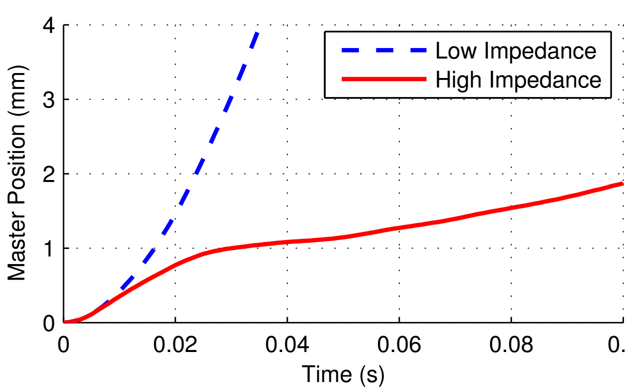


Fig. 5. Master response under a 2 N external force with low ($\eta = 0\%$) and high ($\eta = 100\%$) impedance level

Equivalently, the user feels the sensation of controlling a light slave through a compliant coupling. In the high impedance case, the master accelerates slowly and oscillations of the virtual coupling between the master and slave inertias are apparent, giving the user a sense of a larger inertia controlled through a much tighter interface.

IV. Experiments and Results

We performed user experiments with our 1-DOF telerobotic system under two cases: A) fixed, high impedance and B) variable impedance. For comparison, the first case represents most current telerobotic systems, which try to achieve transparency with a tight master-slave coupling. It is the user's responsibility to limit impact forces by moving slowly. The experiments were carried out by a trained user who had explored and practiced strategies for both the variable and fixed impedance telerobotic systems.

A. Experiment 1: Pressing against the Environment

In the first experiment, the user is asked to carefully make contact with and then apply a constant force to the environment of approximately 15 N. The resulting force, velocity, and impedance profiles are plotted in Figure 6.

In the fixed impedance case, the user approaches contact more slowly, in order to lessen the magnitude of the impact force spike. Once in contact the user pushes on the master, transferring the force to the slave via the PD coupling. For the variable impedance strategy, the user begins in freespace and grips the master lightly, creating a low impedance on the slave device. This low impedance mitigates contact forces as the slave impacts the environment. Once in contact, pushing the master device against the virtual PD coupling results in higher grip forces and a higher impedance. We see that the variable impedance strategy is performed faster yet produces lower impact forces. Also note that the user, by selecting low freespace impedance, has sacrificed precise position tracking which is not relevant to the task objective.

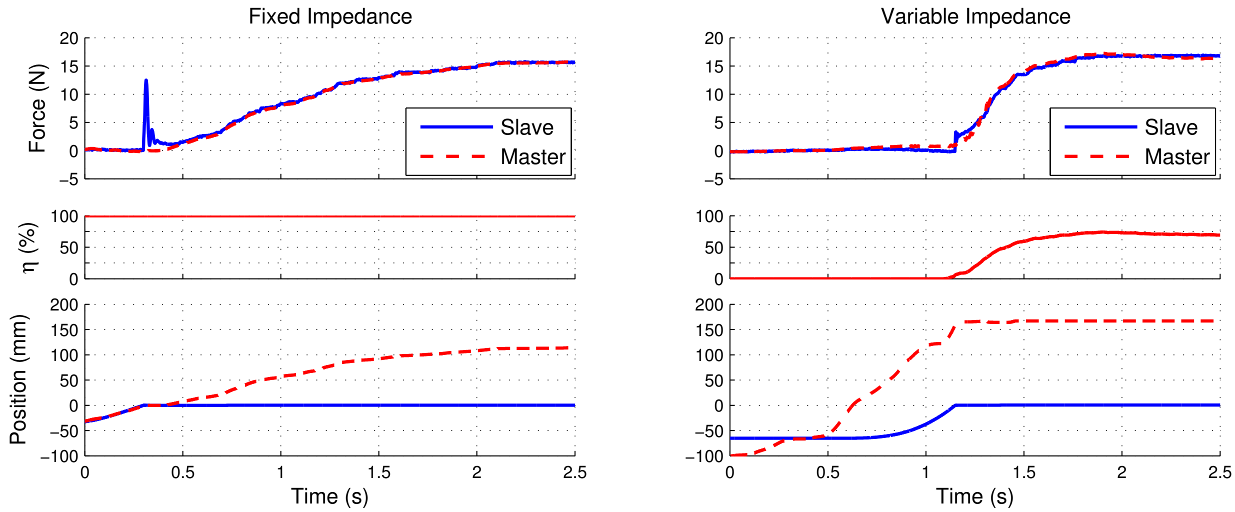


Fig. 6. Experiment 1: The user contacts the environment to achieve a desired force. The impact force is lower and the steady state force is achieved more quickly under variable impedance control.

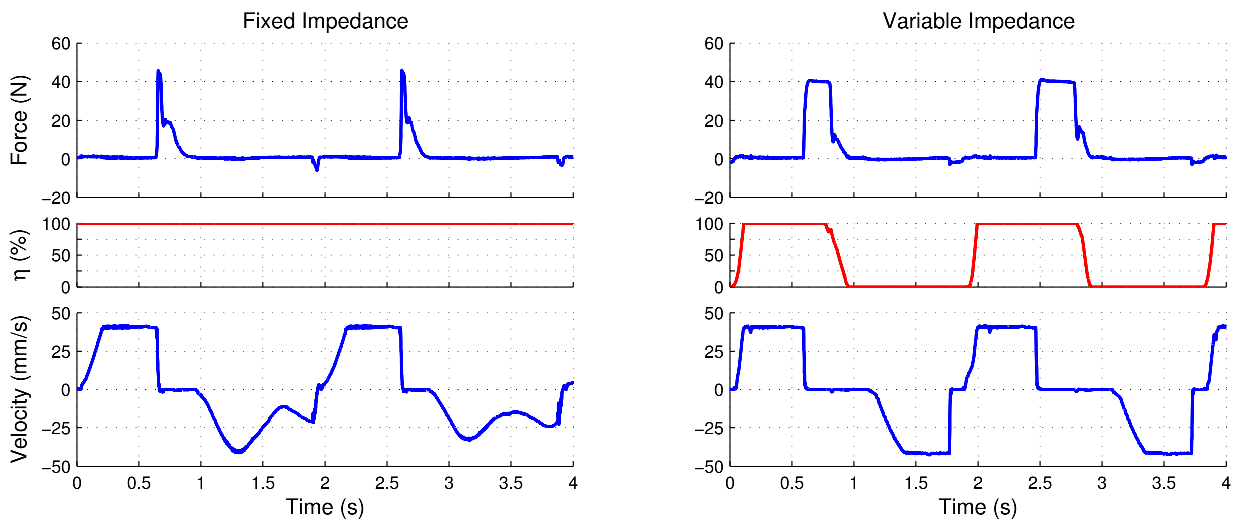


Fig. 7. Experiment 2: The user alternates hard and light impacts. The fixed impedance case requires careful velocity modulation to create light impacts.

B. Experiment 2: Alternating Hard and Light Impact

This experiment illustrates the user's ability to naturally and quickly change behaviors, simulating a task which involves both gentle and firm interactions. The user is asked to make a hard impact with the environment at one end of the slave's workspace and then to make a light contact with the environment at the other end of the workspace. Characteristic force, velocity and impedance profiles are presented in Figure 7.

For the fixed impedance case, the user creates a hard impact by quickly moving the master to one end of the workspace. The impact creates a large force spike, and the user quickly reverses direction toward the light contact end. While approaching the light contact, the user slows down, carefully regulating velocity to create a small impact force.

For the variable impedance case, the user creates a hard impact by gripping the master tightly and moving it quickly. The tight grip during the hard contact lessens the rebound, providing a more stable contact illustrated by the sustained contact force. To create soft contact, the user loosens his grip and moves the master quickly in the other direction. The low impedance guarantees that impact will not create large forces, so the user approaches with maximum speed.

Note the simplicity of the variable impedance strategy. The user does not need to carefully control the motion of the slave relative to the contact. Instead, the operator can execute the task nearly open loop.

C. Experiment 3: Time Constrained Hard and Light Impacts

To characterize the user's ability to vary interactions with the remote environment over a range of task speeds, the user is asked to perform hard and light impacts as before but timed to a beat provided by a metronome. The user is

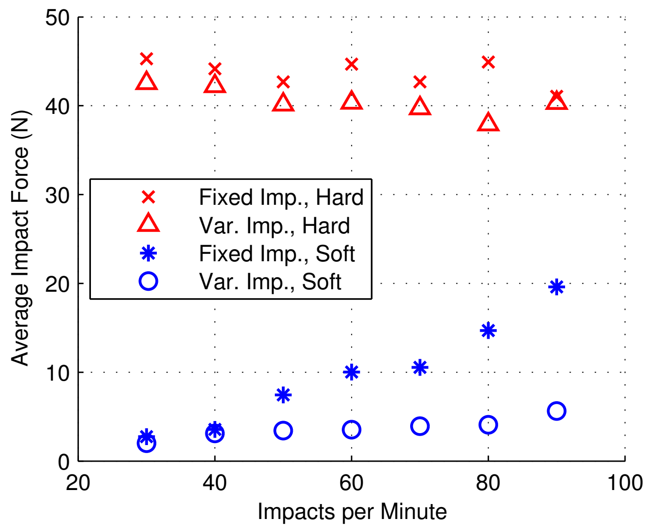


Fig. 8. Experiment 3: Time constrained impacts show failure of fixed impedance control strategies at high speeds

asked to apply as light and hard an impact as possible while maintaining the speed of the selected tempo. The average magnitude of the impacts is plotted in Figure 8.

For the fixed impedance device, the average magnitude of the light impacts increases with task speed as impact velocities inevitably rise. Additionally, at higher tempo the user experiences an increased incidence of error, often failing to make contact with the environment at all.

With the variable impedance device, the user is able to maintain low impact magnitudes at high speed. The magnitudes of the hard impacts are slightly reduced due to a clutch design issue whereby the necessary MR fluid activation level for maximum impedance can only be achieved under a sustained magnetic field.

This experiment suggests that, as task speed increases, the user is unable to perform the precise motion control required to make light impact with the fixed impedance device. With the variable impedance device, the user identifies the task, sets the impedance appropriately, and is then able to perform the task with less focus.This experiment may suggest that the cognitive load for the high impedance motion control strategy is higher than for the variable impedance control strategy.

V. Conclusion

Robots in unstructured environments must possess interaction capabilities ranging from gentle to firm. Humans achieve this range through physical variation of impedance.

We suggest a telerobotic architecture with an extra impedance command channel and implicit haptic feedback of the actual slave impedance. The impedance command may be derived from the sensed user impedance or an additional, intuitive input, such as grip force. The architecture also includes a slave robot with variable impedance actuation, as software gains alone cannot affect the high frequency impedance which determines impact forces and safety.

Experiments were carried out by a trained user in 1-DOF with a grip force sensing master and a variable impedance MR fluid clutch actuator. They suggest the user employs different, simpler, and more intuitive strategies when performing tasks with the new channel of impedance information. These new strategies allow the user to vary impedance to suit task requirements. For example, the user can deliberately lower impedance to sacrifice position tracking but ensure low impact forces. Or, they may raise the impedance to generate large forces and precise motions.

We hope this work illustrates some of the benefits of variable impedance teleoperation. We believe users can ultimately complete a greater range of tasks, not only more safely but also with lower cognitive effort. Extensions to multi-degree of freedom will follow, perhaps using a single impedance command to scale impedance matrices. In the future we hope telerobotic systems will allow more intuitive and effective utilization of human skills.

Acknowledgment

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