Improving Telerobotic Touch Via High-Frequency Acceleration Matching

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Abstract*— Humans rely on information-laden high-frequency accelerations in addition to quasi-static forces when interacting with objects via a handheld tool. Telerobotic systems have traditionally struggled to portray such contact transients due to closed-loop bandwidth and stability limitations, leaving remote objects feeling soft and undefined. This work seeks to maximize the user's feel for the environment through the approach of acceleration matching; high-frequency fingertip accelerations are combined with standard low-frequency position feedback without requiring a secondary actuator on the master device. In this method, the natural dynamics of the master are identified offline using frequency-domain techniques, estimating the relationship between commanded motor current and handle acceleration while a user holds the device. During subsequent telerobotic interactions, a high-bandwidth sensor measures accelerations at the slave's end effector, and the real-time controller re-creates these important signals at the master handle by inverting the identified model. The details of this approach are explored herein, and its ability to render hard and rough surfaces is demonstrated on a standard master-slave system. Combining high-frequency acceleration matching with position-error-based feedback of quasi-static forces creates a hybrid signal that closely corresponds to human sensing capabilities, instilling telerobotics with a more realistic sense of remote touch.

I. Introduction

While vision provides us with spatial information about the world, we use the sense of touch primarily to ascertain material properties such as hardness and texture [1]. During typical manual interactions, the human hand experiences a broad spectrum of forces ranging from steady state to one kilohertz. These signals are detected by a rich array of mechanoreceptors in the skin, muscles, and joints, naturally guiding both dexterous and exploratory interactions. High-frequency transients are particularly useful during tool-mediated interactions, providing information about macroscopic material properties as well as fine surface features.

For over fifty years, teleoperation has promised users the ability to manipulate and perceive a remote environment as though it were directly accessible. Using a robot arm as the user's proxy at the remote site, a telerobotic system acts as an extended tool, leveraging the operator's skills and decision-making abilities into a setting beyond normal reach. Such technology enables humans to safely handle toxic waste, assemble space equipment from Earth, and operate on the heart through tiny incisions. While the heritage of industrial robotics has enabled such systems to provide accurate position tracking, realistic touch perception of the remote environment remains elusive.

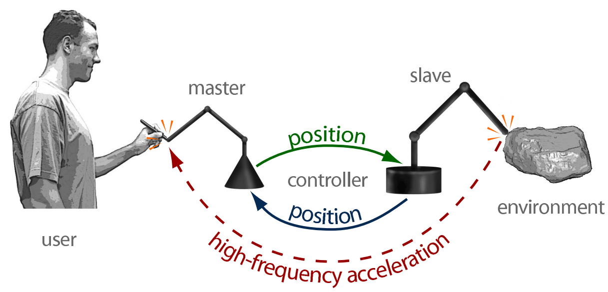

Fig. 1. Overlaying closed-loop position control with high-frequency acceleration feedback allows the user to feel remote objects more adeptly.

Seeking to provide the user with an authentic feel for the objects contacted by the slave, this work develops a new paradigm for telerobotic feedback that accurately transmits the fine vibratory details of contact. The approach of high-frequency acceleration matching augments a standard bilateral position controller with a feedback channel from the slave tip to the master handle, as illustrated in Fig. 1. The high-frequency accelerations that stem from contact with hard or textured objects are measured in real time and re-created at the user's fingertips. While such an effect can be achieved by adding secondary actuators to the handle of the master mechanism [2], [3], the device's main motors serve this purpose beautifully if the dynamic connection from motor to handle is taken into account. We have previously used a similar approach to significantly improve the realism of virtual environments [4], [5], and this paper develops the methods necessary for matching accelerations in real time.

As discussed in Section II, this work builds on earlier findings in haptic feedback for teleoperation and virtual environments. Section III gives a technical overview of the high-frequency acceleration matching approach and describes the telerobotic system on which it has been developed. Section IV explores the dynamic connection from master motor to handle and presents a suitable methodology for offline system identification. A strategy for processing accelerations during real-time operation is laid out and tested in Section V. Finally, Section VI summarizes our current views on acceleration-matched feedback in telerobotics and delineates avenues for further work on this topic.

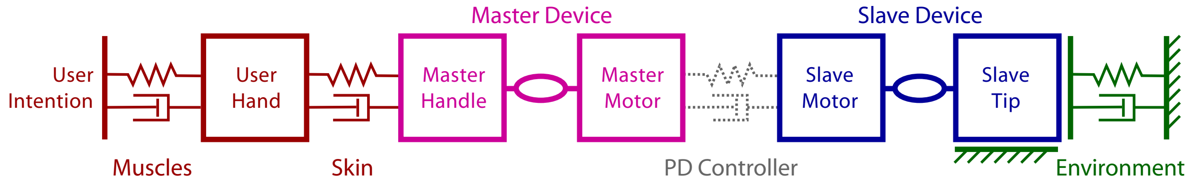

Fig. 2. A lumped parameter model of a telerobotic system under bilateral PD control. The user's influence on the system is approximated as a position set-point attached to the master handle through the arm muscles, hand, and skin. For clarity, only one member is depicted between the endpoint and motor of both master and slave mechanisms, though these connections can include several spring-like, dissipative, and inertial elements.

II. Background

Teleoperation dates back to nuclear research in the 1940s and 1950s, driven by a need for humans to handle radioactive material from behind shielded walls. With the earliest systems, the operator controlled the motion of the manipulator through an array of on-off-on switches, for example flipping a lever to the right to begin clockwise wrist rotation [6]. Providing no natural movement mapping and no indication of remote forces, these manipulators were difficult to operate, leading Goertz to build pairs of master-slave robots whose motions were mechanically linked via gears and cables. These new systems allowed the operator to move the master and thus the slave with normal hand motions, feeling forces and vibrations from the remote interaction through the connecting structure.

Though a significant improvement over a switch-based interface, the mechanical connection was soon replaced by electrical signals for increased flexibility [7], to the detriment of user perception. Bilateral proportional-derivative (PD) control was used to connect the two manipulators, attempting to emulate the direct mechanical connection of earlier systems [8]. This simple control scheme creates a virtual spring and damper between the motors of the two devices, and it is the most commonly used control method in today's telerobots.

A single degree-of-freedom PD-controlled master-slave system is illustrated in Fig. 2, showing the long dynamic chain that connects the user to the environment. Under bilateral control, the master and slave robots form a closed-loop system that has its own dynamics; sensor discretization, actuator dynamics, time delay, and structural compliance all compromise the stability of such a system at high gain, limiting closed-loop bandwidth to about five to 20 Hz, e.g. [9]. Although this control methodology adequately transmits intentional hand motions and quasi-static forces, it cannot convey the high-frequency dynamic response of a stiff or textured environment, as illustrated in Fig. 3. Without high-frequency haptic feedback, all items feel like soft, smooth foam, and users must rely on visual or auditory cues to ascertain material properties.

In the alternative strategy of position-force control, the slave moves under PD control, and its environmental contact force is measured and replayed to the user by the master mechanism. Although it provides a more direct path from environment to user and hides the slave's friction and inertia, this architecture suffers from contact instability, as feedback forces trigger master motions that excite further contact forces. Forces must typically be attenuated to prevent closed-loop feedback from driving the system unstable [10], again trading off stability and performance. Additionally, all high-frequency feedback forces are distorted by the dynamic chain between the master

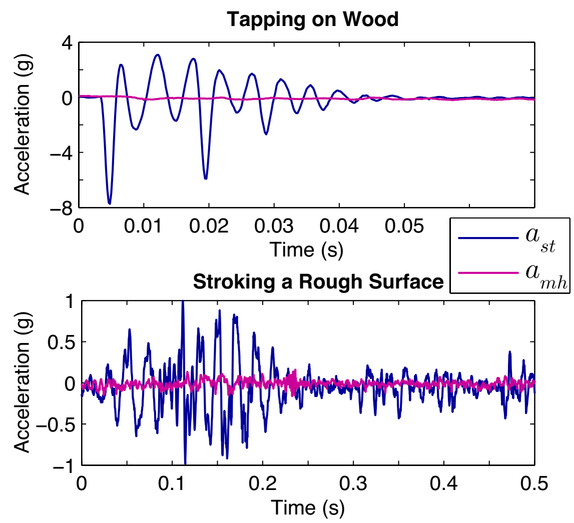

Fig. 3. Slave tip and master handle accelerations, a_{st} and a_{mh} respectively, do not match when tapping on a piece of wood or stroking a roughly textured object under bilateral proportional-derivative control.

mechanism's motors and the human's hand. This chain often includes several lightly damped structural resonances, which distort the user's haptic perception of the remote environment and interfere with material and texture identification. Despite its drawbacks, position-force control does allow the user to receive some high-frequency feedback during contact with remote objects, improving discrimination of material properties.

Many researchers have recognized the human affinity for high-frequency feedback and have worked to improve the quality of the user's perception in both virtual reality and teleoperation. Lawrence et al. distinguished between the stiffness of virtual walls, analogous to low-frequency position feedback in telerobotics, and their perceptual hardness [11], defining the metric of rate-hardness to quantify a virtual wall's ability to display quickly changing forces at contact [12]. Okamura et al. took advantage of this principle by displaying decaying sinusoid transients at key moments during virtual tapping, stroking, and puncturing tasks [13], [14], improving perceived realism and task completion. We extended this event-based haptics approach and introduced the method of pre-recorded acceleration matching, achieving near realistic user ratings for virtual wood [4], [5]. These studies show that a combination of vibration and force feedback, displayed simultaneously via the master mechanism's motors, heightens perception capabilities for material discrimination tasks in virtual environments.

Similar benefits have been obtained by displaying vibrations via the master device in teleoperation, though stability must also be monitored. Kontarinis and Howe overlaid accelerations

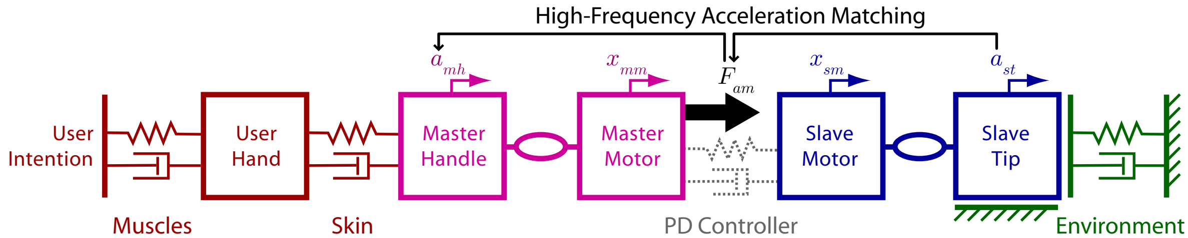

Fig. 4. In the proposed approach, an additional force, F_{am}, matches the high-frequency accelerations of the master handle, $\tilde{a}_{mh}$, to those of the slave tip, $\tilde{a}_{st}$, while a standard PD controller provides the user with low-frequency haptic feedback.

measured at the slave's end-effector with traditional position-position feedback via a supplementary voice coil actuator mounted near the user's fingertips [2]. Careful placement of this vibrating element, as well as the purposeful use of an intervening compliance, allowed them to decouple the feedback and command paths, preventing closed-loop instability. User tests indicated that this hybrid feedback strategy increased user performance in inspection, puncturing and peg-in-slot tasks, and later work improved the vibration actuator for better rendering of contact transients [3].

To avoid closed-loop instability, other researchers have tried to provide force cues via the alternative means of sensory substitution. Massimino presented low-frequency force information to users of a telerobotic system using audio as well as vibrotactile information, finding an improvement over visual feedback alone [15], [16], although the auditory and vibrational waveforms used in these studies mapped frequency to contact location rather than to the dynamics of the impact itself. In another approach, Hawkes measured accelerations at the slave robot fingertips, playing the signal to the operator via headphones [17]. Both of these methodologies circumvent the closed-loop stability problems posed by high-frequency force feedback, but they therefore cannot capitalize on the user's natural expertise at touch-based interactions.

III. Overview

Recognizing the sensory importance of high-frequency signals, we have developed a new approach to haptic feedback in telerobotics. Modeled after Daniel and McAree's frequency separation of human manipulation [18] and also reminiscent of Tanner and Niemeyer's approach to improving telerobotic perception [19], we combine a low-frequency power band with a high-frequency information band, divided at approximately 20 Hz. Although PD control alone cannot convey high-frequency accelerations to the user's fingertips, it adeptly handles quasi-static feedback. As illustrated in Fig. 4, the method of acceleration matching adds a secondary feedback channel based on the slave tip acceleration, creating a hybrid controller that is better suited to human sensing capabilities.

Typical hand motions such as tapping and stroking are slower than 10 hertz and can be communicated between sites via bilateral PD control using the motor position signals x_{mm} and x_{sm}. The high-frequency dynamic response of the environment, which contains frequencies generally on the order of several hundred hertz, is measured via the acceleration of the slave tip, a_{st}. During tool-mediated interactions, accelerations such as these strongly stimulate the Pacinian corpuscles in the human fingertips [20] and provide rich information about an object's properties, including geometry, texture, and material composition. During teleoperation, we apply an additional force, F_{am}, at the master motor to attempt to match the high-frequency acceleration of the master handle, $\tilde{a}_{mh}$, to that of the slave tip, such that

$$\tilde{a}_{mh}(t) = \tilde{a}_{st}(t), \tag{1}$$

where the tilde signifies a high-pass-filtered signal.

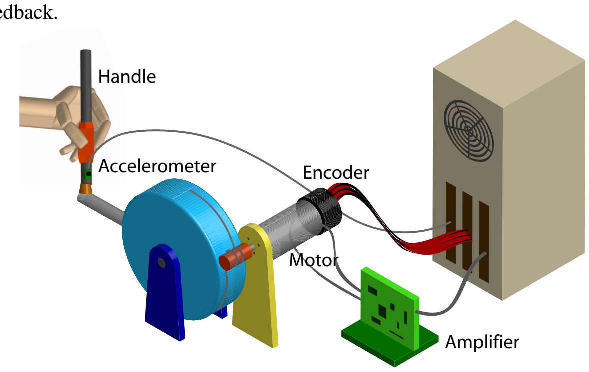

Fig. 5. Many dynamic elements intervene between the master's requested motor current, i_{mm}, and its measured handle acceleration, a_{mh}.

Trusting the PD controller to transmit low-frequency forces between the two devices, the acceleration-matching force can impart high-frequency accelerations to the handle through the master device's connecting elements. As illustrated in Fig. 5, the master's motor and handle are attached to one another through a series of cables and linkages that form a complex dynamic system. Additionally, an amplifier attempts to generate the commanded force by applying current to the master motor, a transmission that may also have significant dynamics. Creating specific master handle accelerations by requesting motor current requires knowledge of the dynamics of the user's hand and the master itself; we must understand how commanded motor current, i_{mm}, affects handle acceleration, a_{mh}, defining the following transfer function:

$$G_m(s) = \frac{A_{mh}(s)}{I_{mm}(s)}, \tag{2}$$

where s is the Laplace operator. $G_m(s)$ represents the net electrical, mechanical, and user influence on the creation of high-frequency master handle accelerations. Section IV explores this dynamic relationship and presents system identification techniques that are effective on typical haptic systems.

With a well-identified model of these dynamics, $\hat{G}_m(s)$, the telerobotic controller can perform high-frequency acceleration matching. The real-time measurement of slave acceleration

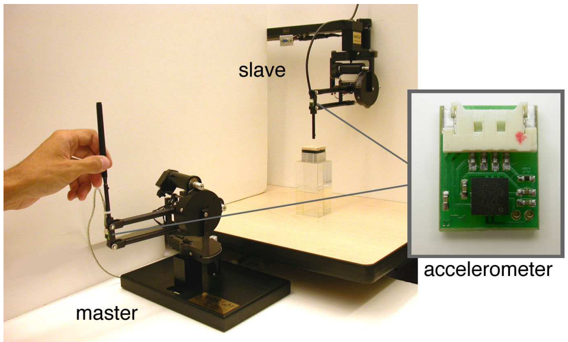

Fig. 6. The telerobotic testbed includes accelerometers at the endpoints of both the master and the slave.

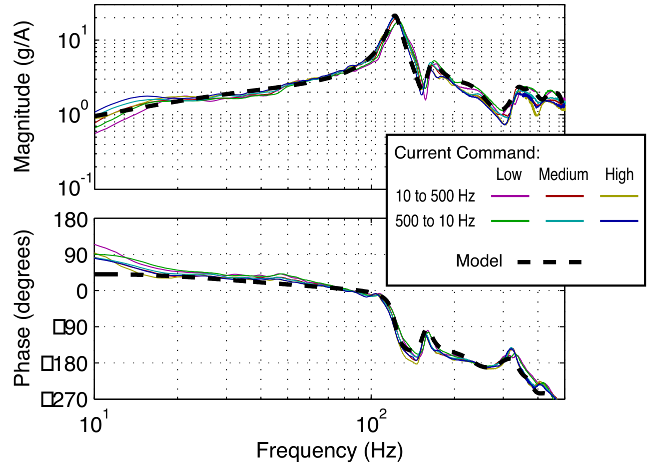

Fig. 7. The master's frequency-domain relationship between commanded current and measured handle acceleration for six different input signals is well modeled by $\hat{G}_m(s)$.

must be processed to extract the meaningful high-frequency content, yielding $\tilde{a}_{st}$. The identified master model can then be inverted to determine the necessary current request, choosing

$$I_{mm}(s) = \frac{1}{\hat{G}_m(s)} \tilde{A}_{st}(s). \quad (3)$$

Section V investigates this process of matching high-frequency accelerations in real time, showing results from tapping on a hard object and stroking a rough texture.

The master-slave system on which this research was conducted consists of a pair of early Phantom® robots by SensAble Technologies. As pictured in Fig. 6, each device has three degrees of freedom, and each joint was connected to the corresponding joint on the other device via PD control. This work focused on adding high-frequency acceleration matching to the vertical axis, which runs along the length of the handle and bears primary responsibility for tapping feedback. Acceleration matching could be added to the other joints through replication of the current work. The shoulder and elbow joints of the master mechanism were driven with high-bandwidth linear amplifiers, and the system's other four axes were driven by standard pulse-width modulation amplifiers. The system was controlled at a five kilohertz servo rate by a desktop computer running RTAI Linux.

Master and slave accelerations were measured by rigidly attaching a MEMS accelerometer to the endpoint of each device. As shown mounted on a custom printed circuit board in the inset of Fig. 6, the ADXL321 chip from Analog Devices provides a range of ± 18 g, an adjustable bandwidth that was set at one kilohertz, and a footprint of just 16 square millimeters. Care was taken to minimize electrical noise on the accelerometer lines by using a clean power source and shielded cables, buffering the signals before the analog-to-digital conversion, and tying unused analog inputs to a stable voltage. This telerobotic system, with its pair of accelerometers, served as an excellent testbed for the development of the high-frequency acceleration-matching approach.

IV. Characterizing User-Master Dynamics

High-frequency acceleration matching requires a good model of the relationship between commanded motor current and measured handle acceleration. As discussed in Section III and depicted in Fig. 5, these dynamics depend on the behavior of the master's current amplifier, the master's mechanical elements, and the user's hand. We seek a linear, time-invariant model, $\hat{G}_m(s)$, that closely approximates the behavior of our complex electro-mechanical system above about 20 hertz. Though such a model can be obtained in many ways, non-parametric identification techniques are particularly well suited to this purpose, as they do not assume a model order.

Although many researchers characterize the dynamic-response of haptic devices by applying sinusoids at individual frequencies, e.g. [14], [21], we prefer the elegance and speed of the empirical transfer function estimate (ETFE) approach [22]. Our input signal was a linearly varying swept sinusoid in commanded current, chosen to excite a specified range of frequencies in the target system. The low- and high-frequency limits were set at 10 and 500 hertz, staying an order of magnitude slower than our servo rate of five kilohertz. Swept sinusoids of three different magnitudes and with both low-to-high and high-to-low frequency order were applied to the system while a user held the stylus in a comfortable grip. We standardized the user's influence by requesting a steady hand position and a moderate grip force; such variations can be accounted for by repeating the identification at other grip force levels [23], but this measure was not deemed necessary for validating the use of acceleration matching in teleoperation. Each input signal was two seconds long, and four trials were taken for each of the six input signals, reversing the sign of the signal for two trials. The requested master motor current, $i_{mm}(t)$, and the sensed master handle acceleration, $a_{mh}(t)$, were recorded for each trial.

The frequency-domain behavior of the user-master system can be illuminated by computing the ETFE for each set of trials. The 10,000-point discrete Fourier transform (DFT) is computed separately for each input and output signal. The DFT of each output is then divided by the DFT of its input, and results are averaged in the complex domain for each input signal's set of trials. The magnitude and phase of these results can be viewed as experimentally determined Bode plots, and the ETFEs for our six test conditions are shown as the solid, colored lines in Fig. 7. The striking agreement across input signal magnitude and frequency order indicates that our master system behaves approximately linearly; some deviations are observed below 20 hertz, where user intention dominates, and above 200 hertz, where nonlinear stiffness and dissipation may increase response magnitude for small input signals.

A linear, time-invariant model can be fit to these experimental results by hand-tuning the placement of poles and zeros; the model developed for our system is shown as the black dashed line in Fig. 7. At steady state, we would expect the user-master system to behave like a spring, providing the transfer function from requested current to handle acceleration with two zeros at the origin. Although identification of low-frequency dynamics is obscured by the user's reaction to the input, we do observe an approximate slope of plus two at 10 hertz, along with a phase lead of about 90 degrees. For our model, which is concerned primarily with behavior above 20 hertz, a single zero at five hertz was deemed sufficient, followed by a pole at 25 Hz; we avoid placing zeros at the origin for $\hat{G}_m(s)$ because they become pure integrators when the transfer function is inverted.

The system's primary resonance occurs near 122 Hz and is followed by alternating pairs of lightly damped zeros and poles. When fitting a linear model to such results, both magnitude and phase should be considered, adding in a small time delay to further depress the phase at high frequency. If magnitude and phase cannot both be matched (an indication of underlying nonlinearities), the model should follow the magnitude trace; we hypothesize that users are more sensitive to errors in acceleration magnitude than they are to phase errors, though this distinction merits further investigation. Similarly, when the ETFE curves diverge, we fit the model to match the curves with the highest magnitude to avoid over-stimulating resonant behavior.

To facilitate real-time inversion, the model should have a relative degree of zero, i.e. it must have the same number of poles as zeros. Extra zeros should be added just above the frequency range of interest to achieve this effect, adjusting the rest of the model to match the data accordingly; our model contains a pair of zeros at 800 hertz with a damping ratio of 0.5 for a total of 15 poles and 15 zeros. Having a finite gain at high frequency ensures that the inverse model will not infinitely amplify high-frequency noise in the slave acceleration signal. While it is difficult to determine the exact origins of the identified dynamics, models obtained through this procedure provide a good estimate of the high-frequency behavior of a haptic system.

V. Matching Accelerations in Real Time

Once the relationship between the master's current command and handle acceleration has been characterized, the model can be used to perform high-frequency acceleration matching during telerobotic interactions. The measured slave tip acceleration, a_{st}, is processed and applied to the inverse master model, $1/\hat{G}_m(s)$, as shown in Fig. 8 along with sample signals. The inverse master model has relatively large gain at high frequency, so the slave acceleration signal must first be smoothed to rid it of any high-frequency electrical noise. Our system uses a fifteen-point modified Bartlett-Hanning window,

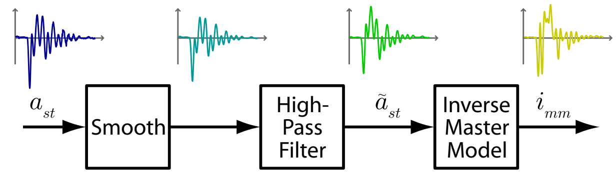

Fig. 8. Signal processing of slave acceleration includes smoothing, high-pass filtering, and model inversion.

which adds a fixed delay of seven time steps but preserves the shape of important high-frequency transients. We hypothesize that a human user, whose reaction time is approximately 150 milliseconds [24], will not notice a feedback delay this small, though it may affect the system's stability.

The smoothed acceleration signal is then high-pass filtered to prevent overlap with the low-frequency power band. The PD controller is responsible for transmitting movement below the tracking bandwidth of the slave's sub-system, and the acceleration-matching channel should not interfere. Furthermore, the high-frequency feedback channel should not attempt to recreate free-space accelerations that stem from user movement, so this high-pass filter should always be set above 10 Hz. Our system uses a second-order linear filter with a bandwidth of 22 hertz, well matched to the second-order low-pass behavior of our slave's PD controller and significantly above the range of human intention. The discrete-time equivalent of this filter is applied in real-time to the system's smooth slave acceleration signal, producing the high-frequency version, $\tilde{a}_{st}$, that we want to replicate on the master.

To determine the necessary current request, the smoothed, high-pass-filtered version of the slave tip acceleration is then applied to the inverse of the identified master model. Without including time delay, the continuous model, $\hat{G}_m(s)$, is inverted and discretized, using a Tustin approximation to preserve stability. The resulting model is then added to the real-time controller, using double-precision floating point calculations to avoid numerical instability. With such a process in place, a telerobotic controller can then determine the current command necessary to match the master handle's high-frequency accelerations to those of the slave tip.

High-frequency acceleration matching was added to the shoulder axis of our master-slave system, and sample results for tapping on wood and stroking a rough texture are shown in Fig. 9. The system successfully portrays the slave tip's high-frequency accelerations to the user, creating a haptic experience that is significantly more rich than that created by PD feedback alone, which was illustrated in Fig. 3. In the acceleration-matching approach, differences between slave and master accelerations stem from smoothing, high-pass filtering, and inaccuracies in the master model. Although this algorithm has not yet been evaluated in a formal user study, we believe that acceleration matching vastly improves the user's ability to determine the material or texture of the environment, as accomplished by the similar strategy and secondary actuator of Kontarinis and Howe [2]. Anecdotally, users have enjoyed the improved sense of telerobotic touch that high-frequency acceleration matching provides, commenting that it makes the system feel more like a rigid tool.

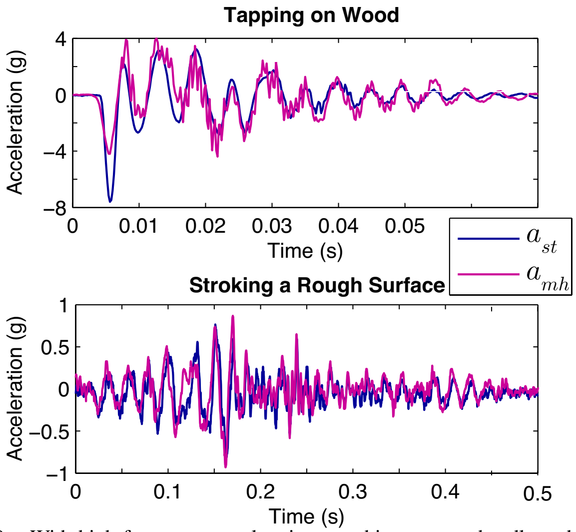

Fig. 9. With high-frequency acceleration matching, master handle and slave tip accelerations correspond well. Note that the intervening time delay of 2.2 milliseconds was removed to enable visual comparison of the two signals.

VI. Conclusion

Together with low-frequency forces sensed in the muscles and tendons, high-frequency accelerations provide important manipulation cues that must be rendered by high-fidelity telerobotic systems. Adding high-frequency acceleration matching to systems under bilateral PD control allows the user's fingertips to experience the same high-frequency accelerations as the slave's end effector. Rather than feeling like soft, smooth foam, hard remote objects feel crisp, and textured objects feel rough. The user can take advantage of his or her vast experience with everyday manipulations to interpret these signals and adjust the interaction accordingly.

The presented methodology takes advantage of the master mechanism's existing actuators to accurately transmit high-frequency vibrations to the human's hand. This technique requires a good dynamic model of the relationship between master current command and handle acceleration, which can be obtained via offline frequency-domain identification. The real-time telerobotic controller then computes the necessary current command by applying a smoothed, high-pass-filtered version of the slave tip acceleration to the inverse master model. At present, the dynamics of the user-master system have been fully characterized for only two users, each of which was asked to maintain a comfortable grip on the handle; further work will be required to determine whether user-specific or grip-modulated models are required for robust operation. A criterion for system stability and more sophisticated signal processing techniques, such as adaptive high-pass filtering, will also be explored.

While we have demonstrated the technical viability of this technique and can anecdotally vouch for its improved feel, a formal human subjects experiment is the necessary next step. High-frequency acceleration matching will be added to the other two axes of our telerobotic system, and tests including material and texture discrimination with and without acceleration matching will be conducted. We are confident that users will be able to feel remote objects more adeptly with acceleration-matched feedback, and we look forward to developing this approach further.

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