Proceedings of IMECE 2004
2004 ASME International Mechanical Engineering Congress and RD&D Expo
Anaheim, California, USA, November 13-19, 2004

IMECE2004-60049

CANCELING INDUCED MASTER MOTION IN FORCE-REFLECTING TELEOPERATION

Katherine J. Kuchenbecker **Günter Niemeyer**
Telerobotics Lab
Stanford University
Stanford, California 94305
http://telerobotics.stanford.edu
{katherine.kuchenbecker, gunter.niemeyer}@stanford.edu

ABSTRACT

Providing the user with high-fidelity force feedback has persistently challenged the field of telerobotics. This paper presents a new approach for achieving stable, high-gain force reflection via cancellation of the master mechanism's induced motion. In a classic position-force controller, high force-feedback levels drive the system's internal master-slave loop unstable during contact with the remote environment. Lowering the force-feedback gain ensures stability but diminishes the haptic cues available to the user, masking contacts and preventing hard objects from feeling appropriately stiff. The proposed cancellation approach permits high levels of force feedback by attenuating only the controller's internal loop. Using a model of the master mechanism's response to applied force feedback, an estimate of induced high-frequency movement is subtracted from the master's measured position to approximate the user's intended path for the slave. The cancellation technique is described, modeled, and validated herein, including testing on a one-degree-of-freedom telerobotic system. It is shown to improve the feel of the system, tripling the testbed's achievable force-feedback gain without compromising stability.

1 INTRODUCTION

Originally developed for applications such as nuclear decommissioning and construction in space, teleoperation gives a user direct control over the motions of a robot manipulator situated in a remote environment. The telerobotic system acts as an extended tool, leveraging the human's skill set and decision-making ability into an environment that humans normally cannot reach. In order to facilitate easy interactions, such systems are designed to reproduce the manipulation experience as authentically as possible for the user, seeking to maximize his or her level of telepresence [1]. Two main factors that contribute to this performance metric are the accuracy of the remote slave robot's position tracking and the fidelity of the force feedback provided to the user via the master robot.

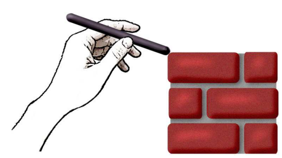


Figure 1. TOOL-MEDIATED FORCE FEEDBACK.

Traditionally, most telerobotic systems have focused on providing excellent tracking capabilities, and force feedback has been a secondary consideration [2]. Both channels are crucial to creating a transparent interaction, though, because both are central to direct manipulation. As illustrated in Fig. 1, the user of a traditional tool feels interaction forces immediately, as they are transmitted to the hand through the tool. The human explores the environment by moving the tool around, using his or her highly developed sense of touch to discern geometric and material properties of the structures involved.

During teleoperation, the controller on the master mecha-

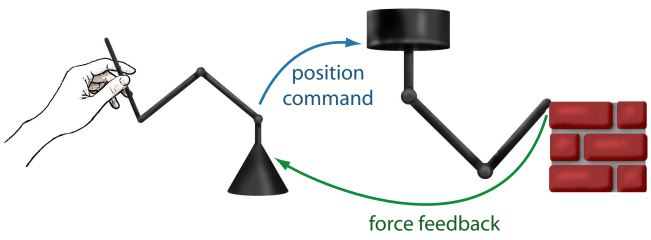


Figure 2. TELEROBOTIC FORCE FEEDBACK.

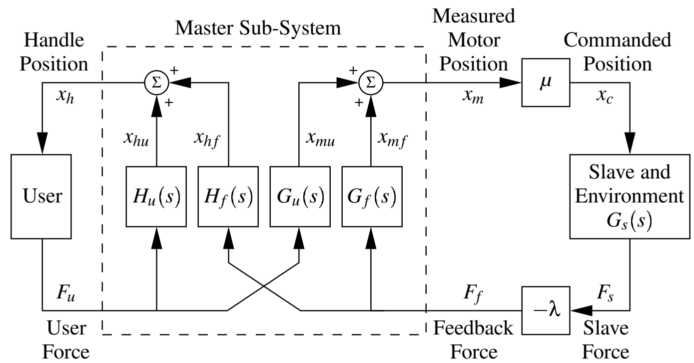


Figure 3. POSITION-FORCE CONTROL ARCHITECTURE.

nism works to recreate the experience of direct manipulation for the user. It commands the slave to track the user's position and simultaneously applies artificial reaction forces to the hand, as illustrated in Fig. 2. Conveying high-frequency, transient forces is particularly important to the transparency of the interaction. These signals occur when the user initiates contact with a stiff element of the environment like metal, wood, or stone. Increasing almost instantaneously at contact, such reaction forces often resemble an exponentially decaying sinusoid, strongly stimulating the mechanoreceptors in the user's fingertips. Research has shown that portraying such signals increases the realism and dexterity of haptic interactions [3–5], but present telerobotic systems can seldom convey such nuanced force feedback.

This paper presents a new strategy for providing high-fidelity force reflection without compromising system stability. Similar to control techniques such as feedback linearization, this method uses model-based cancellation to remove induced master motion from the slave position command. After examining the behavior of a standard position-force controller in Section 2, this paper reviews previous approaches to force-feedback stabilization in Section 3. The proposed controller modification is described, implemented, and tested in Sections 4, 5, and 6, respectively. Section 7 draws conclusions from the described findings and suggests avenues for future work on this new approach to telerobotic force feedback.

2 POSITION-FORCE CONTROL

A standard position-force architecture is illustrated in Fig. 3, showing user, master, slave, and environment. The controller monitors the position of the master mechanism's motors, x_m, and commands the slave robot to move accordingly via x_c. The resulting behavior of the slave robot and the remote environment are lumped into the element $G_s(s)$. The controller also measures the force experienced by the slave's end-effector, F_s, and displays this feedback via the motors on the master device as F_f. The forward position scaling ratio, μ, and the force feedback gain, $-\lambda$, can be used to scale the interaction between the two sites, following the convention of [6]. Most interestingly, choosing $\lambda > \mu$ amplifies feedback forces for increased user sensitivity, which may be valuable for material discrimination tasks and delicate operations such as microsurgery.

Our analysis centers on the dynamics of the master subsystem, which must perform both input and output functions. During a telerobotic interaction, the user and the controller both apply forces to this mechanism. The user's interaction force, F_u, is applied at the master's endpoint, and the feedback force, F_f, is applied at its motors. Each of these two forces affects both the handle position, x_h, and the motor position, x_m, through the transmission elements that connect them. With a linear model, this behavior may be characterized by four transfer functions, which represent natural device properties such as inertia and flexible transmission dynamics. This treatment of master motion specifically distinguishes between x_{mu}, motor movement caused by the user force, and x_{mf}, motor movement caused by the feedback force, giving them the separate transfer functions $G_u(s)$ and $G_f(s)$.

During an interaction, the master robot must simultaneously observe the position of the user's hand and apply reaction forces to it, but these functions are coupled via the device dynamics, $G_f(s)$. This coupling creates a problem inherent to all force-reflecting telerobotic systems; when force feedback is applied to the master console, the master robot moves regardless of the user's intention. This pathway closes a signal loop inside the controller, allowing high-frequency induced motion to interact with system lag and drive the entire system unstable. This performance limitation is governed by the transfer function of the controller's internal loop,

$$G_{loop}(s) = \mu\,\lambda\,G_f(s)\;G_s(s). \tag{1}$$

Stability is ensured if the loop gain remains below unity ($|G_{loop}(j\omega)| < 1$) when the lag exceeds 180° ($\angle G_{loop}(j\omega) < -180°$). Communications time delay, which will not be considered in this investigation, adds phase lag at all frequencies, decreasing stability margins accordingly.

A high force-feedback gain λ provides strong haptic cues to the user but also destabilizes environmental contact by increasing the loop gain. Instability typically arises when the slave robot encounters a stiff object in the remote environment; feedback of the large, high-frequency reaction force induces motion of the master device that is overlaid with the user's intended movement. This measured high-frequency motion is treated as a slave position command, which in turn alters the feedback force. When the system's gain and lag cause loop instability, the remote tool repeatedly makes and breaks contact with the environment, and the master manipulator shakes the operator's hand unnaturally.

This phenomenon may also be examined from the viewpoint of momentum and energy transfer. The forces that result from a collision between slave and environment change the slave's momentum, which the force feedback duplicates on the master. To avoid violating conservation laws, the product of μ and λ must be less than or equal to m_m/m_s, where m_m and m_s are the effective masses of the master and slave, respectively, as identified by Daniel and McAree [6]. System stability strongly depends on the magnitude of the controller's loop gain.

Implementing a simple position-force controller without modifying $G_f(s)$ and $G_s(s)$ requires selecting μ and λ to avoid contact instability. The forward position scale μ is usually chosen to equate the workspace volumes of master and slave or to provide motion scaling important to the task. The force reflection ratio λ is then increased from zero until contact instability arises. Standard telerobotic systems controlled in this manner set λ to values much less than unity, attenuating all force feedback signals equivalently [7]. Encountered objects thus feel like foam or rubber rather than wood or metal. Gone is the crispness that characterizes true contact, as well as the increased telepresence afforded by this sensation.

3 PREVIOUS APPROACHES

Many researchers have addressed the trade-off between stability and force feedback, proposing a variety of approaches for preventing contact instability during teleoperation. These strategies all aim to modify the behavior of the system's internal feedback loop. Three compensation approaches are illustrated in Fig. 4, including local derivative feedback on the master, a forward position command filter, and a feedback force filter. The block diagram omits handle position for clarity.

The first approach for suppressing induced master movement is to add viscous damping to the master manipulator via local feedback [8, 9]. Augmenting the block diagram with negative derivative feedback from x_m to F_f changes the system's loop transfer function to

$$G_{loop}(s) = \mu\,\lambda\,\frac{G_f(s)}{1+bsG_f(s)}\,G_s(s). \tag{2}$$

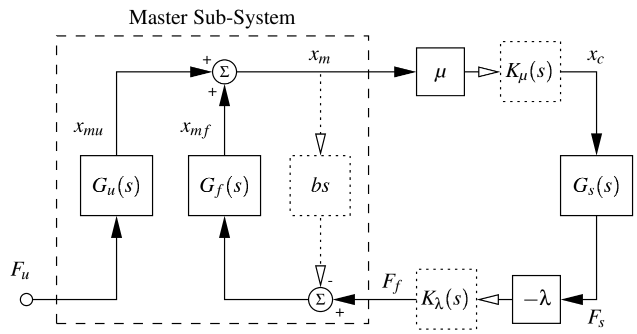


Figure 4. POSITION-FORCE CONTROL ARCHITECTURE WITH THREE COMPENSATION OPTIONS: LOCAL DERIVATIVE FEEDBACK ON MASTER POSITION VIA bs, POSITION COMMAND FILTER $K_\mu(s)$, AND FORCE FEEDBACK FILTER $K_\lambda(s)$.

Although it can stabilize contact, this added damping is also apparent to the user and makes the system feel slow and unresponsive, even when the slave is moving in free space. In addition, this strategy requires a clean, accurate measurement of velocity, which is seldom available in systems that rely on numerical differentiation of discrete position signals.

Other researchers have explored the possibility of low-pass or notch filtering the slave's commanded position via $K_\mu(s)$ [10, 11]. The loop transfer function then becomes

$$G_{loop}(s) = \mu\,\lambda\,K_\mu(s)\;G_f(s)\;G_s(s). \tag{3}$$

This technique attenuates the position command's destabilizing mid- to high-frequency content, but it can also prevent the slave from tracking quick movements by the user. The resulting system can feel unresponsive, which again detracts from the transparency of the interaction. Additionally, the filter must be carefully tuned to avoid adding too much lag at low frequency, which would compromise the system's stability margins.

Another stabilization strategy involves low-pass or notch filtering the force feedback signal via $K_\lambda(s)$, removing mid- to high-frequency content before display on the master mechanism [6, 12]. This compensator yields

$$G_{loop}(s) = \mu\,\lambda\,K_\lambda(s)\;G_f(s)\;G_s(s). \tag{4}$$

Filtering the force feedback can stabilize a system, but it also masks any high-frequency force signals from the user, resulting in interactions that feel soft and undefined. Such a choice enables stability under higher force reflection ratios, but it compromises the information content of the feedback signal, especially when initiating contact with a stiff environment.

The feel of a system with filtered force feedback can be improved by using a separate actuator to display the signals re-

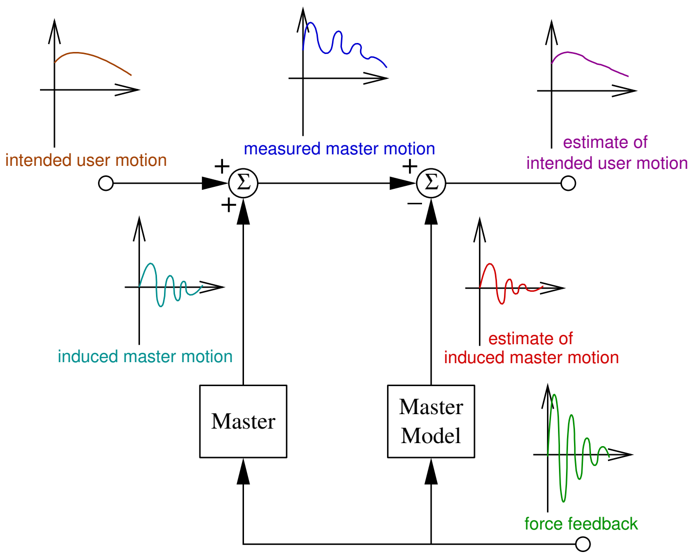


Figure 5. CANCELLATION OF INDUCED MASTER MOTION (CIMM) VIA MODEL-BASED ESTIMATION OF TRANSMISSION DYNAMICS.

moved by $K_\lambda(s)$, a technique often described as combined vibrotactile and force feedback [3]. This frequency-domain separation increases the information available to the user while maintaining system stability. It should be noted that the vibrations from the additional actuator must be carefully isolated from the forward position command so that they do not enter the closed loop and incite contact instability.

Beyond these four standard approaches, some unique alternatives have also been considered. The controller described by McAree and Daniel [13] anticipates collisions between the slave and the environment using external optical sensors. When contact is imminent, the controller actively reduces the slave's velocity to minimize the forces generated, effectively adjusting $G_s(s)$ in real time. This approach requires less force-feedback filtering than an uncompensated system does, allowing the user to feel more mid-frequency signals; however, this adjusted slave behavior can be disorienting to some users [13].

Another strategy involves continually predicting the user's intended position command via a model of the human rather than using the presently measured master position. Explored options range from polynomial and spline extrapolation [14] to a full human arm model with measured neural inputs [15]. Most such efforts have difficulty achieving high-bandwidth position tracking, which is imperative for transparency, but the focus on human intention rather than measured master position is intriguing. Clearly, the dynamic interaction between human, master, slave, and environment merits further exploration.

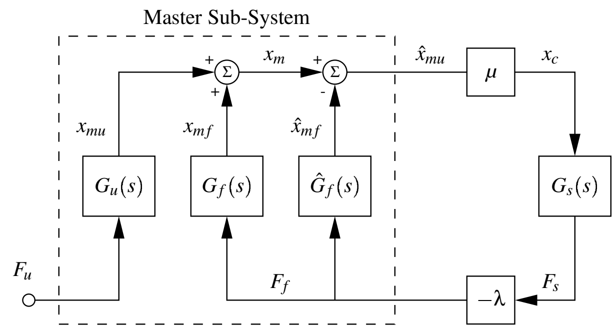


Figure 6. POSITION-FORCE CONTROLLER WITH CANCELLATION.

4 PROPOSED APPROACH

Whereas most prior research has focused on shaping loop dynamics, we propose a strategy for breaking the controller's problematic internal loop. Contact instability can potentially be avoided by distinguishing between the two types of master movement: that which results directly from user commands, x_{mu}, and that which is induced by force feedback, x_{mf}. In the ideal implementation of this algorithm, the slave is commanded to follow the path that the user intended for it, rather than the measured position of the master mechanism. As depicted conceptually in Fig. 5, unattenuated, unfiltered forces are applied to the user via the master mechanism motors, and an estimate of the motion that will result is computed from a system model. This motion is then subtracted from the measured device movement to provide an estimate of the user's intended path.

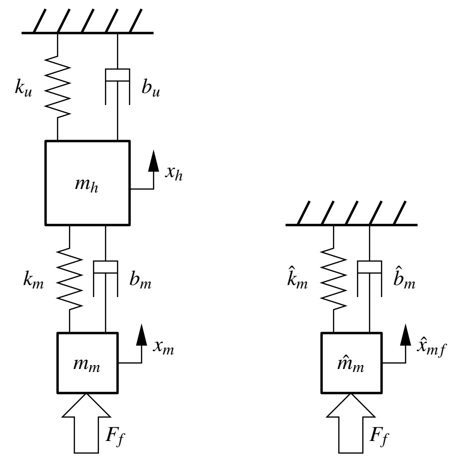
When this modification is added to the standard position-force controller discussed in Sec. 2, the master side takes the form of the block diagram in Fig. 6, where $\hat{G}_f(s)$ is the system's model of the master mechanism's response to force feedback. The commanded slave position is thus given by

$$x_c = \mu\,\hat{x}_{mu} = \mu\left(x_{mu} + G_f(s)F_f - \hat{G}_f(s)F_f\right). \tag{5}$$

The loop transfer function of the cancellation approach is

$$G_{loop}(s) = \mu\,\lambda\left(G_f(s) - \hat{G}_f(s)\right)G_s(s). \tag{6}$$

If the model $\hat{G}_f(s)$ is closely matched to the natural system $G_f(s)$, the magnitude of the resulting $G_{loop}(s)$ will be small. Controller performance will be best when the chosen model slightly under-estimates the response of the master; as seen in Eq. 6, over-estimation creates a negative gain, which can destabilize the feedback loop and should be avoided. With good cancellation of induced master motion, the loop gain of the system will be attenuated, and stability margins will be improved. The user will be able to feel the full range of forces experienced by the



(a) Full Model (b) Cancellation Model

Figure 7. FULL AND REDUCED MASTER MODELS WITH TRANSMISSION DYNAMICS BETWEEN HANDLE AND MOTOR.

slave end-effector, but the cancellation will essentially decouple the force feedback from the forward path.

The success of this strategy obviously depends on the accuracy of the master mechanism model; $\hat{G}_f(s)$ needs to adequately characterize the dynamic relationship between feedback force, F_f, and unintended motion of the master motor, x_{mf}, during a telerobotic interaction. In this situation, the user will be holding the handle of the device, and the feedback force will be applied at the motor. A lumped parameter model of this system is illustrated in Fig. 7 (a). The masses of the handle and motor, m_h and m_m, are typically connected via cables and linkages that are somewhat flexible, acting as a stiff spring, k_m, with light damping, b_m. The user's joint dynamics will behave approximately like a soft spring, k_u, and damper, b_u, connecting the handle to ground [2, 16–18], a model that has been validated as a good predictor of passive hand motion during haptic interactions [19].

The master system depicted in Fig. 7 (a) has two resonant modes. First, the two masses can vibrate in unison against the biomechanical impedance of the user. In this mode, the motor and the handle move in phase with one another at a low frequency, usually slower than 10 Hz. This motion falls within the human actuation bandwidth, so the user can actively resist this type of unintended motion; consequently, we do not seek to cancel this resonant mode. Indeed, contact instability typically arises as high-frequency oscillations at many tens of Hertz, an order of magnitude faster than this biomechanical resonance.

In the mode that compromises system stability, the handle and the motor move in opposition to one another, 180° out of phase. As haptic devices typically have stiff transmission elements, this resonance tends to occur at much higher frequencies than the biomechanical resonance, often approaching 100 Hz. The resulting induced master motion significantly increases the system's high-frequency loop gain, driving most position-force controlled systems unstable under high gain-product $\mu\lambda$. This undesirable behavior depends on device parameters such as motor inertia and cable stiffness and is relatively unaffected by user impedance and intention.

Isolating the destabilizing high-frequency mode from the system's dynamic response is the key to obtaining a good model for the cancellation approach. The model $\hat{G}_f(s)$ needs to be most accurate for the frequency range near crossover, where the uncompensated system goes unstable and the loop gain most needs attenuation. Notably, the model does not need to perform the difficult task of predicting human response at low-frequency; rather, it should drastically underestimate movement below 10 Hz to avoid interfering with the user's active motions. Instead it should capture the high-frequency mode that stems from internal structural dynamics. This oscillation can be well approximated by the second-order model shown in Fig. 7 (b) with appropriately selected parameters $\hat{m}_m$, $\hat{b}_m$, and $\hat{k}_m$. No model can be perfect, but one that captures the general dynamic behavior of this mode will provide significant loop gain attenuation near crossover and improve system performance.

5 SYSTEM IDENTIFICATION

The proposed cancellation approach was applied to a position-force controller on an existing telerobotic system. Because induced master motion occurs at the motor level, a one-degree-of-freedom (dof) testbed was chosen to represent the internal dynamics that occur on every axis of higher-dof manipulators. Results from this simple case will minimize the effects of configuration dependency and dynamic cross-coupling, elucidating instead the behavior of the proposed controller modification.

Two Immersion Impulse Engine 2000™ joysticks were configured as a single-axis master-slave system under position-force control, as pictured in Fig. 8. The joysticks provide high-resolution position measurement via optical encoders and high-fidelity actuation via DC motors and a gear-reducing cable drive. An ATI Mini40 force sensor is located beneath the front trans-

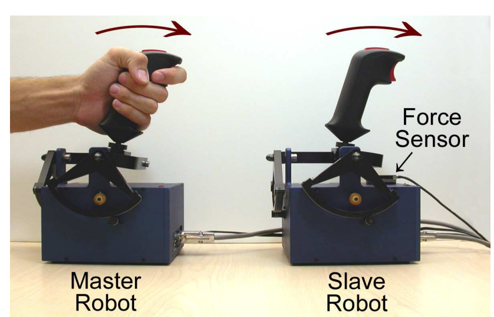


Figure 8. ONE-DOF POSITION-FORCE TESTBED

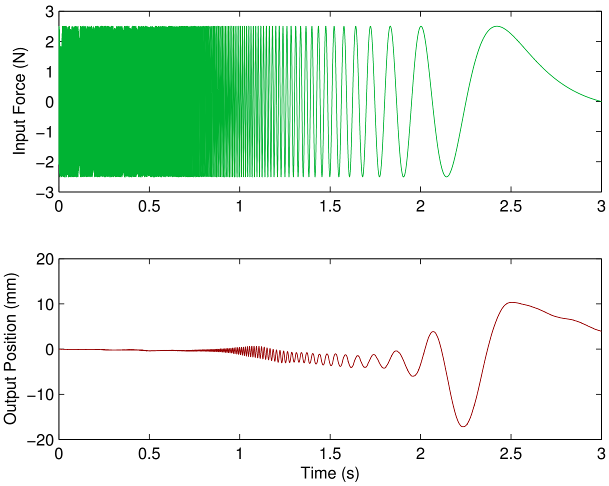


Figure 9. SWEPT SINE WAVE INPUT AND MASTER RESPONSE.

mission element of the slave joystick so that the contact force between it and the slave can be measured throughout an interaction. The hardware is controlled by a desktop computer running RTAI Linux. A 5 kHz servo loop is used to read the force sensor and the master and slave encoders, compute master and slave control forces, and output current commands to the motors. Similar optical encoders, cable drives, force sensors, and servo loops are used in most telerobotic systems.

Standard system identification techniques can be used to determine how applied forces will affect the position of the master device during use. For this system, spectral analysis was used to identify the frequency-response characteristics of the master joystick when held by a user in a comfortable grip, following the methods presented in [18]. This technique compares the frequency content of a force input signal with that of the system's corresponding position output using discrete Fourier transforms (DFTs). A three second long swept sine wave, starting at 200 Hz and ending at 0.1 Hz, is applied by the motor to excite the system, and the resulting movement is measured by the encoder on the motor's shaft. Fig. 9 shows the input and output signals for identification of the master mechanism, which exhibits the two expected resonant modes and significant attenuation at high frequency. The empirical transfer function estimate (ETFE) is then formed by dividing the DFT of the output signal by that of the input. To reduce noise, the ETFEs from three tests are averaged together in the complex domain, and the resulting magnitude and phase values are smoothed using a boxcar filter. The resulting diagram, given in Fig. 10, can be viewed as an experimentally determined Bode plot.

The shape of the master's frequency response corresponds to that of a fourth-order system of relative degree two, identified as the full model in Figs. 7 (a) and 10. It has a biomechanical resonance at 3 Hz and an internal structural resonance at 70 Hz.

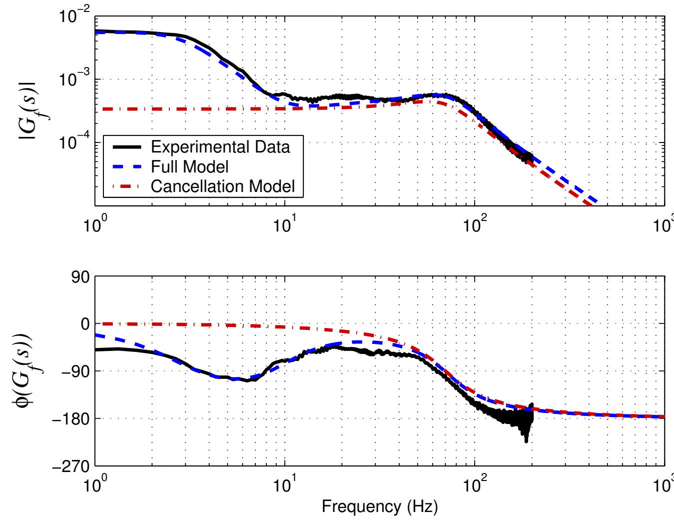


Figure 10. MEASURED AND MODELED MASTER BEHAVIOR.

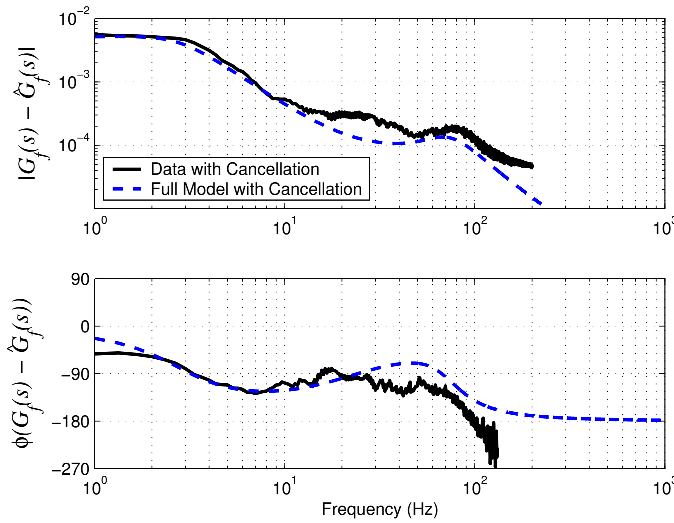


Figure 11. MEASURED AND MODELED CANCELLATION.

Following the arguments of Sec. 4, the system's high-frequency behavior is closely matched by a reduced model that focuses on mechanism dynamics, shown as the cancellation model in Figs. 7 (b) and 10. This model includes effective motor mass $\hat{m}_m$, transmission damping $\hat{b}_m$, and transmission stiffness $\hat{k}_m$.

$$\hat{G}_f(s) = \frac{\hat{x}_{mf}}{F_f} = \frac{1}{\hat{m}_m s^2 + \hat{b}_m s + \hat{k}_m} \tag{7}$$

As seen in Fig. 10, the two models closely match the empirical data in both magnitude and phase, which suggests that linear modeling adequately describes this system's behavior. Discrep-

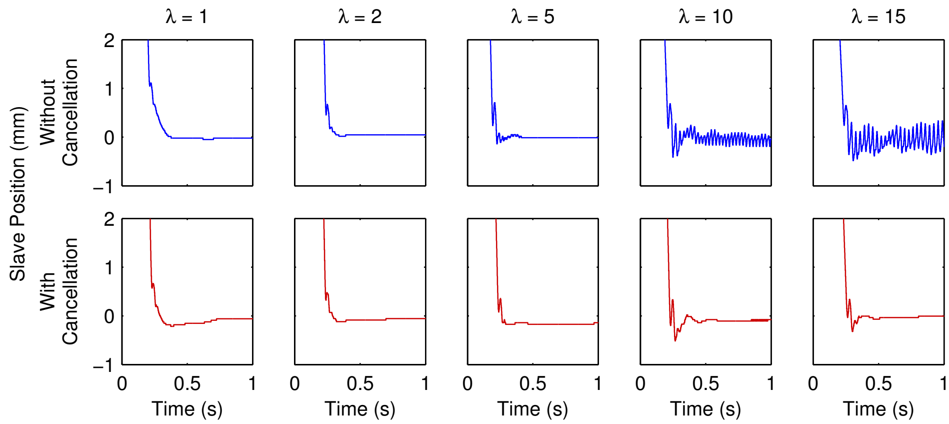


Figure 12. MOTION OF SLAVE MANIPULATOR AT HARD CONTACT WITH AND WITHOUT CANCELLATION.

ancies appear at high frequency where unmodeled effects such as finite encoder and force sensor resolutions and the discrete sampling period of the control loop begin to deteriorate system performance. Other factors such as coulomb friction, non-linear stiffness, and backlash also contribute to the observed differences in magnitude and phase. A more sophisticated master model could capture these effects, enabling more complete attenuation of the loop transfer function.

Modeling accuracy can also be examined via the level of cancellation achieved by the identified model. The system's response to the applied swept sine wave was predicted and subtracted from the measured position output, as would be done by the proposed controller. The ETFE of this signal, $\hat{x}_{mu}$, is compared to the Bode plot of the full model transfer function with cancellation in Fig. 11. Canceling the master motion predicted by the reduced model does indeed lower the magnitude of the master transfer function by a factor of three in the frequency range of interest. The experimental data's behavior under cancellation resembles the response of the cancellation-enabled full model, though its attenuation power is more modest due to non-linearities in the real system. The level of agreement between the model and the experimental data is encouraging and indicates that the cancellation strategy may provide significant stability and transparency improvements when implemented on a real telerobotic system.

6 TESTING

A preliminary performance evaluation of the proposed cancellation architecture was tested via implementation on the joystick testbed. The transmission dynamics model $\hat{G}_f(s)$ identified in Sec. 5 was discretized using a Tustin approximation and used to implement cancellation in the real-time servo loop. A series of tests was then conducted on the system's response to hard contact between the slave and the force sensor, performed with and without cancellation of induced master motion, under various levels of force reflection and no position scaling ($\mu = 1$).

Results are shown in Fig. 12 as sample traces of the slave's position during contact. The beginnings of contact instability are observed with the standard controller at $\lambda = 5$, and stable contact becomes impossible much beyond this point. These oscillations are removed from the system when cancellation is applied, allowing stable contact beyond $\lambda = 15$. This finding corresponds to tripling the available force feedback to the operator while maintaining stable contact conditions, enabled by the three-fold reduction in loop gain at crossover seen in Fig. 11. Cancellation also improves the feel of the interface, providing crisper force signals without generating distracting vibrations.

7 CONCLUSION

Position-force control in teleoperation is presently limited by the controller's internal loop, which allows force feedback to contribute to the slave's position command. Breaking this connection is imperative for providing higher fidelity force feedback while maintaining the requisite system stability. A new method for preventing high-gain contact instability was presented, in which a simple model of the master's response characteristics is used to estimate and cancel out the motion caused by force feedback signals. Initial results provide a three-fold increase in stable force reflection gain, indicating that the proposed method can facilitate higher fidelity force feedback than that which is available using a simple position-force algorithm.

The dynamic model of the master needed to implement this technique depends only on parameters inherent to the device, which makes the approach independent of user characteristics. The model is dominated by high-frequency transmission dynamics and is easy to obtain using standard system identification methods. Linear models have performed well despite their simplicity; for example, the cancellation technique was also tested on a master mechanism that includes significant transmission backlash, and it provided improvements equivalent to those presented in Sec. 6.

Work is currently under way to refine the master model and include behavior that cannot be linearly approximated. Further work will include characterization of the one-dof testbed's slave and loop transfer functions to better focus the cancellation model at the frequency of contact instability. Continued analysis of the cancellation strategy, particularly in comparison with the existing techniques described in Sec. 3, will elucidate its effects on user experience. Eventually, cancellation controllers that observe and adapt to the system's response during an interaction will also be investigated. Overall, exploring the new strategy of canceling high-frequency induced master motion during position-force control promises to improve system stability and transparency.

ACKNOWLEDGMENTS

This material is based upon work supported under a National Science Foundation Graduate Research Fellowship. The authors thank the reviewers for their astute suggestions and thoughtful commentary.

REFERENCES

[1] Sheridan, T. B., 1992. "Musings on telepresence and virtual presence". Presence, **1** (1) , pp. 120–126.

[2] Hogan, N., 1989. "Controlling impedance at the man / machine interface". In Proceedings of the IEEE International Conference on Robotics and Automation, vol. 3, pp. 1626–1631.

[3] Kontarinis, D. A., and Howe, R. D., 1995. "Tactile display of vibratory information in teleoperation and virtual environments". Presence, **4** (4) , pp. 387–402.

[4] Okamura, A. M., Dennerlein, J. T., and Howe, R. D., 1998. "Vibration feedback models for virtual environments". In Proceedings of the IEEE International Conference on Robotics and Automation, pp. 674–679.

[5] Okamura, A. M., Cutkosky, M. R., and Dennerlein, J. T., 2001. "Reality-based models for vibration feedback in virtual environments". IEEE/ASME Transactions on Mechatronics, **6** (3) Sept. , pp. 245–252.

[6] Daniel, R. W., and McAree, P. R., 1998. "Fundamental limits of performance for force reflecting teleoperation". International Journal of Robotics Research, **17** (8) Aug. , pp. 811–830.

[7] Lawrence, D. A., 1993. "Stability and transparency in bilateral teleoperation". IEEE Transactions on Robotics and Automation, **9** (5) Oct. , pp. 624–637.

[8] Hannaford, B., and Anderson, R., 1988. "Experimental and simulation studies of hard contact in force reflecting teleoperation". In Proceedings of the IEEE International Conference on Robotics and Automation, vol. 1, pp. 584–589.

[9] Bu, Y., Daniel, R. W., and McAree, P. R., 1996. "Stability analysis of force reflecting telerobotic systems". In Proceedings of the IEEE International Conference on Intelligent Robots and Systems, vol. 3, pp. 1374–1379.

[10] Speich, J. E., Fite, K., and Goldfarb, M., 2000. "A method for simultaneously increasing transparency and stability robustness in bilateral teleoperation". In Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2671–2676.

[11] Speich, J. E., and Goldfarb, M., 2002. "Implementation of loop-shaping compensators to increase the transparency bandwidth of a scaled telemanipulation system". In Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2886–2893.

[12] Hannaford, B., 1989. "A design framework for teleoperators with kinesthetic feedback". IEEE Transactions on Robotics and Automation, **5** (4) Aug. , pp. 426–434.

[13] McAree, P. R., and Daniel, R. W., 2000. "Stabilizing impacts in force reflecting teleoperation using distance-to-impact estimates". International Journal of Robotics Research, **19** (4) Apr. , pp. 349–364.

[14] Prokopiou, P. A., Tzafestas, S. G., and Harwin, W. S., 1999. "Towards variable-time-delays-robust telemanipulation through master state prediction". In Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechanisms, pp. 305–310.

[15] Prokopiou, P. A., Harwin, W. S., and Tzafestas, S. G., 1999. "Enhancement of a telemanipulator design with a human arm model". In *Progress in System and Robot Analysis and Control Design*, S. Tzafestas and G. Schmidt, Eds., vol. 243 of *Lecture Notes in Control and Information Sciences*. Springer-Verlag, pp. 445–456.

[16] Kearney, R. E., and Hunter, I. W., 1990. "System identification of human joint dynamics". Critical Reviews in Biomedical Engineering, **18** (1) , pp. 55–87.

[17] Hasser, C. J., and Cutkosky, M. R., 2002. "System identification of the human grasping a haptic knob". In Proceedings, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 171–180.

[18] Kuchenbecker, K. J., Park, J. G., and Niemeyer, G., 2003. "Characterizing the human wrist for improved haptic interaction". In Proceedings of the International Mechanical Engineering Conference and Exposition.

[19] Hwang, J., Williams, M. D., and Niemeyer, G., 2004. "Toward event-based haptics: Rendering contact using open-loop force pulses". In Proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 24–31.