Robust Impedance Shaping Via Bilateral Manipulation

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1. Introduction

An important class of bilateral manipulators is that in which the master and slave manipulators operate on very different length, force, and power scales. This class includes strength-increasing "man-amplifiers" [6] and "extenders" [5], as well as dexterity-increasing "macro-micro bilateral manipulators" (MMBMs) [2,4]. Whereas man-amplifiers date to the early 1960s, MMBMs are of considerably more recent vintage. MMBMs have potentially important applications in microsurgery [1], microassembly, and microchemistry.

The seamless extension of human dexterity to micromanipulation, however, poses a number of interesting problems. One is the choice of an appropriate philosophical approach. For instance, in conventional teleoperation, a prevalent philosophy is that of "telepresence," in which a vast array of sensory channels would give the operator the feeling of being present at the remote location. A typical embodiment of this ideal might include an exoskeletal master and an anthropomorphic slave. The nature of the dexterity enhancement problem suggests a rather different and far more parsimonious philosophy; namely, that the MMBM be treated as a *hand tool*. Although the MMBM may consist of separate master and slave manipulators, operating on very different power and length scales, the operator should have the perception that it is a single entity, identifiable as a knife or tweezers, for instance. Because, in tool use, somatic, kinesthetic, and proprioceptive sensing are experienced through the tool, a large measure of transparency may be achieved via force-reflection and vision alone.

Another problem, which is the main subject of this paper, stems from the dynamics of microsystems. Due to the variable effects of physical scaling laws, the dynamics of microsystems are fundamentally unlike those of macrosystems. For instance, inertias vary according to volume, while viscous drag coefficients vary according to area. Consequently, *geometrically similar micro and macro systems are not dynamically similar.* Thus, while a stereoscopic display may provide a magnified view of the slave and microenvironment, which will appear as the end of a tool and a macroenvironment, the master manipulator cannot necessarily display a magnified impedance (the impedance embodies the "feel" of the environment) which corresponds to that of a reasonable macroenvironment. The question then arises, what scheme for force feedback will optimize the operator's perception of tool use? One candidate scheme is "impedance shaping bilateral control."

2. Impedance Shaping Bilateral Control

To illustrate the difficulties caused by variable physical scaling effects, and to introduce the concept of impedance shaping, a simple example will be given. For the sake of this example, assume that the MMBM is ideal in the sense that it exhibits no dynamics of its own, and is composed of a velocity feedforward channel of scale factor k_ϕ, and a force feedback channel of scale factor k_ε. Then the impedance of the environment felt through the MMBM is $k_\varepsilon k_\phi$ times the actual environment impedance. Suppose, further, that the environment consists simply of a small mass (m_e) immersed in a viscous liquid. The MMBM is to be used for manipulating the mass.

If a visual display system is used to magnify the image of this microenvironment by a certain factor α, then a good choice of the velocity scale factor is $k_\phi = 1/\alpha$. This choice would ensure that the perception of a 1:1 relationship between the position of the tool's endpoint and the position of the tool's handle is maintained (of course, in actual implementation, position control would be required).

The force relation, however, is more complicated. Because mass scales as length cubed, one sensible choice of the force scale might be $k_\varepsilon = \alpha^4$, which would result in an impedance scaling of $k_\phi k_\varepsilon = \alpha^3$. Unfortunately, the viscous forces on the mass vary according to surface area, so that the appropriate scaling of the viscous component of the impedance would be $k_\phi k_\varepsilon = \alpha^2$. The question of which of these scalings to select has no clear answer; any fixed scaling has the disadvantage that the scaled up impedance will feel more sluggish than a geometrically similar macrosystem (assuming invariant material properties).

The idea behind impedance shaping is that individual contributors to the impedance of the microenvironment, such as inertia and drag, may be scaled independently. For instance, in this example, the actual force exerted on the slave is:

$$F_{slave} = m_e \ddot{x}_{slave} + F_{drag}, \tag{1}$$

while the desired apparent behavior (force exerted by the master on the operator) is:

$$F_{master} = (\alpha^3 m_e)\ddot{x}_{master} + \alpha^3 F_{drag}. \tag{2}$$

This behavior may be achieved approximately with the following force feedback law:

$$F_{master} = (\alpha^4 - \alpha^3)\hat{m}_e \ddot{x}_{slave} + \alpha^3 F_{slave}, \tag{3}$$

where F_{slave} is a measure of the total force exerted on the slave by the microenvironment, and $\hat{m}_e$ is an estimate of the environment inertia (which need not be terribly accurate).

This type of control is called "impedance shaping" because it has the effect of not only rescaling, but also reshaping the frequency domain magnitude and phase plots of the environment's impedance. Some notable features of impedance shaping bilateral control are:

- A model of the microenvironment is needed. The structure of this model is very important; the specific parameter values (such as the estimate of environment mass, above) are not critical.
- Impedance shaping, like other types of bilateral control, gives the operator sensitivity to disturbances from the environment; however, the sensitivities to various dynamic effects are graded to exploit the operator's strengths as a manipulator.

A potential weakness of the impedance shaping approach is that it does assume some knowledge of the environment dynamics, whereas telemanipulators are traditionally used in unstructured environments. Although few environments are completely unknown, this is a valid concern, which can be addressed by requiring that the MMBM with impedance shaping bilateral control be *robust.*

3. Robustness

For the purposes of this paper, *a bilateral manipulator is said to be robust if, when coupled to a passive environment, it presents to the operator an impedance which is passive.* Thus, although the impedance presented by the master may depart radically from the actual impedance of the environment, it at least lies within a realm that human operators are known to manipulate successfully.

The robustness criterion as stated above is intuitive, but not easily tested. A version of this criterion which is easily tested was recently published by the author [2]. This version is based upon the recognition that the actual and apparent impedances are related via a *linear fractional transformation*, which can be analyzed with the *structured singular value* techniques developed by Doyle [3]. To use this criterion, the impedance formulation must first be recast in terms of scattering variables [7]. If the MMBM is represented by the following scattering matrix:

$$M(s) = \begin{bmatrix} M_{11}(s) & M_{12}(s) \\ M_{21}(s) & M_{22}(s) \end{bmatrix}$$

then the robustness criterion can be stated as:

Robustness for 2n-Port Teleoperators — A $2n$-port teleoperator with scattering matrix *M(s)* will be guaranteed to exhibit a passive impedance at the master ports when coupled to a passive, but otherwise arbitrary environment at the slave ports, iff:

$$\sup_{\omega}(\mu(M)) = \sup_{\omega}\left(\inf_{\alpha>0} \bar{\sigma}\left(\begin{bmatrix} M_{11} & \alpha M_{12} \\ \frac{1}{\alpha}M_{21} & M_{22} \end{bmatrix}\right)\right) \le 1,$$

where $\bar{\sigma}$ is the maximum singular value, and μ is the structured singular value. Further details and examples are given in [2].

4. A Robust Impedance Shaping Controller

When implemented on an actual master-slave manipulator (see Figure 1), the impedance shaping control law given by Eqn. 3 and $k_\phi = 1/\alpha$ will not result in a robust behavior for any selection of parameter values. This is because both the force and acceleration feedback terms represent *noncolocated* control. A robust controller can be realized, however, simply by replacing F_{slave} with the control force applied to the slave, and rolling off the acceleration feedback term. Moreover, the acceleration feedback term can be used to compensate for the effects of slave inertia. A block diagram of the robust controller is shown in Figure 1.

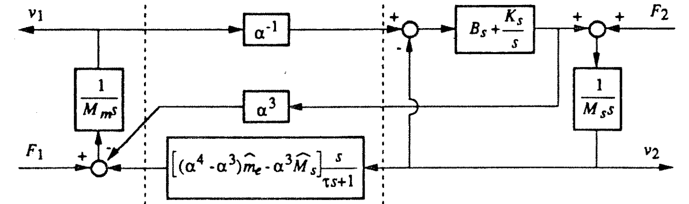

Figure 1. Block diagram of a 1-channel MMBM with robust impedance shaping control. F_1 and v_1 represent force and velocity at the operator port; F_2 and v_2 at the environment port. M_m is the mass of the master, M_s the mass of the slave, B_s and K_s are parameters of a servo controller local to the slave, τ is the bandwidth of the acceleration feedback term.

For the purposes of illustration, the following parameter values are chosen: B_s and K_s make the slave critically damped, with poles at $s = -1/\tau_s$; $\hat{m}_e = 1.5M_s = M_m/\alpha^3$; $\alpha = 10$; $\tau = 5\tau_s$. The admittance of the MMBM is normalized (in frequency, by $1/\tau_s$; in magnitude, by τ_s/M_m), and the structured singular value computed. This result is shown in Figure 2 (bottom). To illustrate the consequences of impedance shaping, the following are displayed in Figure 2 (top): the admittance of an inertial/viscous environment; the admittance as felt throught the MMBM with impedance scaling but not shaping; and the admittance as felt though the MMBM with impedance shaping. Both controllers reduce the apparent admittance of the environment; however the scaling controller does not alter the relative contributions of inertial and viscous effects, except through the parasitic addition of master and slave inertias, while the shaping controller provides additional inertia amplification (shown by the reduction in rolloff frequency) and cancellation of the parasitic slave inertia. These plots have been normalized to the bandwidth of the slave, which can be considerably higher than that of the operator, ensuring that shaping effects are implemented over a sufficiently broad frequency range.

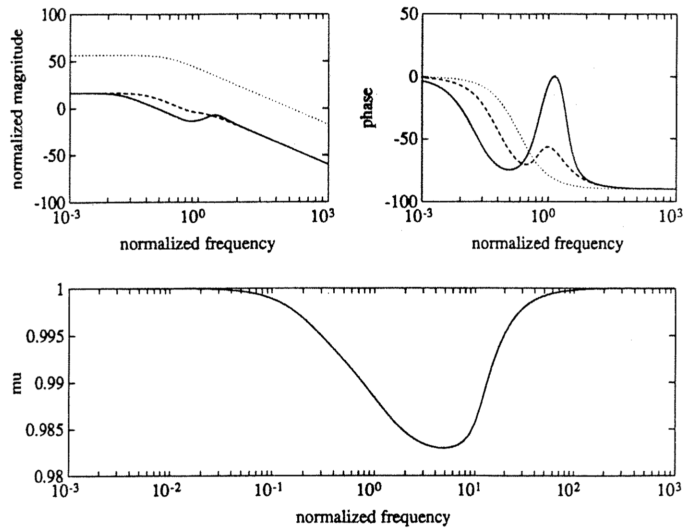

Figure 2. Top — magnitude and phase plots of the admittance a microenvironment (dotted); this admittance felt with an impedance scaling MMBM (dashed), and this admittance felt with and impedance shaping MMBM (solid). Bottom — structured singular value of the MMBM with impedance shaping bilateral control, indicating robustness.

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