A Design Framework for Teleoperators with Kinesthetic Feedback

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***Abstract*—A teleoperator is a pair of robot manipulators connected in such a way as to allow an operator handling one manipulator (the master) to operate on a remote environment (via the slave). Feedback from slave to master increases the realism with which the operator interacts with the environment. Two-port models have been extensively used for the analysis of circuits in which bidirectional energy flows are present at two distinct pairs of terminals. This paper applies the hybrid two-port model to teleoperators with force and velocity sensing at the master and slave. The interfaces between human operator and master, and between environment and slave, are ports through which the teleoperator is designed to exchange energy between the operator and environment. By computing or measuring input–output properties of this two-port network, the hybrid two-port model of an actual or simulated teleoperator system can be obtained. It is shown that the hybrid model (as opposed to other two-port forms) leads to an intuitive representation of ideal teleoperator performance and applies to several teleoperator architectures. Thus measured values of the *h* matrix or values computed from a simulation can be used to compare performance with the ideal. The frequency-dependent *h* matrix is computed from a detailed SPICE model of an actual system, and the method is applied to a proposed new architecture.**

INTRODUCTION

WHEN robotic manipulators are applied to less structured tasks, control is typically divided between automatic and manual functions. Even when advanced automatic control is available, teleoperation (manual control) of the manipulator must be provided as a backup or supplement. Teleoperation, in which the operator gives direct commands to the manipulator, is greatly enhanced if some form of kinesthetic feedback is provided. In a typical example, a joystick senses the operator's position and motors provide backdrive forces and torques to the operator. Such systems are called "bilateral" because information flows in two directions between the operator and the robot.

This paper describes an analytical method which provides a useful characterization of bilateral teleoperators. The method is based on the two-port model of network theory [1]-[4] which is a useful linear representation of complex networks which exchange energy with other networks at two distinct pairs of terminals—ports. Raju and Sheridan [5] have previously developed a two-port model of the position-error-based classical teleoperator using the impedance matrix or "*Z* parameter" formulation. This paper uses the hybrid or "*H* parameter" model to analyze teleoperator systems which have force sensing available at the master and slave.

The two-port hybrid model relates forces and velocities at the input and output ports with a 2 × 2 matrix *h*. The elements of *h*, which are frequency-dependent, are well-understood quantities such as gains, impedances, and admittances. The two-port hybrid parameters can be derived from the system architecture and thus can be used to relate components or parameters of the system to overall system performance.

Bilateral teleoperation has been physically realized [6], [7] and is currently under active development, but true control fidelity has been hampered by slow computer hardware and the use of standard industrial manipulators. Thus the state of the art is such that we need to look at system performance as a whole through a framework which allows prediction of performance from component level information.

Impedance control [8] is a promising control law which addresses the issue of energetic interaction between the manipulator and environment. In a later section of this paper, the author proposes bilateral impedance control, in which local control loops at the master and slave sides attempt to reproduce the impedance seen at the opposite end of the teleoperator. This may ameliorate problems previously associated with time-delayed bilateral teleoperation [9].

This paper concentrates on the analysis of bilateral manipulation in a single degree of freedom. The extension to the full six-axis case allows characterization of the effects of manipulator singularities on teleoperator fidelity.

NOTATION

Complex dynamic systems such as bilateral teleoperation require a uniform description language in which to describe the interaction of electrical, mechanical, and physiological elements. One very general approach is the bond graph method [10], [11] which represents the system as a graph in terms of energy flow (links) and circuit constraints such as Newton's and Kirchhoff's laws (nodes). The state of the system is thus described in terms of the generalized quantities "effort" and "flow." In the most commonly used convention, "effort" represents force and voltage (when it is used to exchange energy rather than information), and "flow" represents velocity and current. In spite of the generality of the bond graph method, the electrical circuit analogy, in which the entire system is transformed into an electrical circuit, was chosen because of the availability and maturity of computer

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Manuscript received January 28, 1988; revised October 18, 1988. This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Part of the material in this paper was presented at the IEEE SMC Conference, Beijing, Peoples' Republic of China, 1988.

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IEEE Log Number 8927079.

1042-296X/89/0800-0426$01.00

programs for electrical circuit simulation. Nevertheless, in discussion of the teleoperator system, it is simplest to retain the terms "effort" and "flow" because teleoperators involve so many forms of transduction. For example, a velocity may be fed back (i.e., multiplied by a constant) to generate a current which, in turn, generates a torque. The model this author has used represents all quantities as either effort or flow. The physical realization of the quantity is implementation-dependent.

MODELING AND SIMULATION

In this paper, development of the analytical framework is complemented by modeling of an actual teleoperator system. The modeling approach is to transform the teleoperation system model into an electrical circuit and simulate it using SPICE, the electronic circuit simulation program developed at UC Berkeley. This approach has been explained in detail by Hannaford and Anderson [9].

Previous teleoperator simulation work has focused on free motion and ignored environmental interaction forces except indirectly. For example, Lee *et al.* [12] performed simulations of the complete teleoperation loop using a simple model of the teleoperator combined with a detailed human operator model. This work resulted in definition of a basic control architecture including kinematic synchronization feedback (feedback of forces and torques proportional to position error) and dynamic synchronization feedback (feedback of forces and torques proportional to the difference between commanded acceleration and the manipulator's configuration-dependent acceleration limit). Other detailed simulation such as that of Eppinger and Seering [13] has focused exclusively on interaction between the arm and environment but not focused on direct human operator control.

TWO-PORT MODEL OF TELEOPERATION

We consider that the design goal is to achieve so-called telepresence in which the operator receives feedback from the manipulator to provide kinesthetic information vital to manipulation. This process can be modeled for a single degree of freedom as shown in Fig. 1. The task of the teleoperator then is to duplicate the effort and flow of the environment at the hand controller and at the same time, to reproduce the effort and flow of the human operator at the manipulator tip. This constrains these efforts and flows to be identical. The dashed lines in the figure represent an ideal teleoperator, i.e., one which has so little distortion or frequency dependence that it is equivalent to direct manipulation of the environment by the operator.

An alternate formulation of the ideal teleoperator is one in which the effort and impedance of the input port are controlled to exactly match the effort and impedance of the environment and vice versa.

The essential design tool is a theoretical framework within which to analyze the effects of teleoperator components on overall system performance. This framework is available in the two-port representation found in the theory of electrical networks. In this model, the complete energetic interaction behavior of a network can be characterized in terms of inputs and outputs measurable at two sets of terminals or ports. In the case of a bilateral teleoperator, these ports are the hand controller handle, and the robotic end-effector. In the two-port model the behavior of the system is completely characterized by measurements of the effort and flow at the two ports. Of these four variables, two may be chosen as independent, and the remaining two, dependent. With the assumption of linearity, the two-port can be represented by a 2 × 2 matrix.

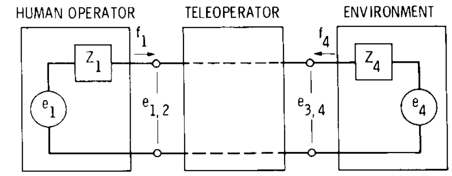

Fig. 1. Two-port model of teleoperator operating into Thevenin equivalent loads representing operator and environment.

For example, Raju and Sheridan [5] have recently analyzed the classical, position-error-controlled teleoperator by designating the two flows (velocities) as independent variables, and the efforts (torques) as dependent. In this case, the control law is characterized by a matrix Z whose elements relate motor torques to the two joint positions

$$\begin{bmatrix} e_{\text{in}} \\ e_{\text{out}} \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} f_{\text{in}} \\ f_{\text{out}} \end{bmatrix}. \tag{1}$$

When output force sensing is available, it is convenient to choose as independent variables e_{out}, the output effort (force), and f_{in}, the input flow (velocity). In this case, the dependent variables are related to the independent variables by the matrix h, the so-called Two-Port Hybrid Parameters

$$\begin{bmatrix} e_{\text{in}} \\ f_{\text{out}} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} f_{\text{in}} \\ e_{\text{out}} \end{bmatrix}. \tag{2}$$

The Two-Port Hybrid Parameters can be used to represent systems which are electrical or mechanical. Because actual teleoperators are complex, electromechanical systems in which, for example, a current may be used to represent or create a force, it is useful to adopt the general nomenclature of Paynter [10] and model energetic interaction using generalized "effort" and "flow." From (2) we can obtain each h parameter by constraining one of the independent variables to zero. The resulting h parameter definitions in the different problem domains are illustrated in Table I.

In Table I, v_j is the voltage at port j, i_j is the current, e_j is generalized "effort," f_j, generalized "flow," $v_{(n)}$ is the voltage at SPICE node n, $i_{(n)}$ the current flowing into the teleoperator at SPICE node n, $F_{\text{in/out}}$ the force, and $x_{\text{in/out}}$ the velocity at the teleoperator inputs and outputs.

The interpretation of the h parameters is

$$h = \begin{bmatrix} Z_{\text{in}} & \begin{array}{c}\text{Rev.}\\ \text{Force}\\ \text{Scale}\end{array} \\ \begin{array}{c}\text{Velocity}\\ \text{Scale}\end{array} & \dfrac{1}{Z_{\text{out}}} \end{bmatrix}. \tag{3}$$

TABLE I
NETWORK REPRESENTATION OF TELEOPERATORS

h Parameter	Electrical	General	SPICE	Mechanical
h_{11}	$\left.\frac{v_1}{i_1}\right\vert_{v_2=0}$	$\left.\frac{e_1}{f_1}\right\vert_{e_2=0}$	$\left.\frac{v_{(100)}}{i_{(100)}}\right\vert_{v(300)=0}$	$\left.\frac{F_{\text{in}}}{\dot{x}_{\text{in}}}\right\vert_{F_{\text{out}}=0}$
h_{12}	$\left.\frac{v_1}{v_2}\right\vert_{i_1=0}$	$\left.\frac{e_1}{e_2}\right\vert_{f_1=0}$	$\left.\frac{v_{(100)}}{v_{(300)}}\right\vert_{i_{100}=0}$	$\left.\frac{F_{\text{in}}}{F_{\text{out}}}\right\vert_{\dot{x}_{\text{in}}=0}$
h_{21}	$\left.\frac{i_2}{i_1}\right\vert_{v_2=0}$	$\left.\frac{f_2}{f_1}\right\vert_{e_2=0}$	$\left.\frac{i_{(300)}}{i_{(100)}}\right\vert_{v(300)=0}$	$\left.\frac{\dot{x}_{\text{out}}}{\dot{x}_{\text{in}}}\right\vert_{F_{\text{out}}=0}$
h_{22}	$\left.\frac{i_2}{v_2}\right\vert_{i_1=0}$	$\left.\frac{f_2}{e_2}\right\vert_{f_1=0}$	$\left.\frac{i_{(300)}}{v_{(300)}}\right\vert_{i_{100}=0}$	$\left.\frac{\dot{x}_{\text{out}}}{F_{\text{out}}}\right\vert_{\dot{x}_{\text{in}}=0}$

In terms of these definitions and interpretations, it is clear that the h matrix representing the ideal teleoperator is

$$h_{\text{ideal}}=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}. \tag{4}$$

This matrix is then a standard by which teleoperator systems can be judged, or by which different configurations of a teleoperator system can be compared. A similar analysis using the Z matrix approach, in which the two flows are the independent variables, gives infinity for each element of Z as a representation of the ideal teleoperator.

Derivation of h Matrix for Two Current Teleoperator Architectures

First I derive the h matrix for the "classical" master–slave teleoperator in which the torque to both master and slave is derived from the position error between master and slave (Fig. 2(a)). This control law is

$$e_{2a}=e_{3a}=(f_1+f_4)G. \tag{5}$$

Considering the first column of h, in which the output effort $e_{3,4}$ is constrained to zero (e.g., the case of free motion of the slave), we have

$$h_{11}=\left.\frac{e_{1,2}}{f_1}\right\vert_{e_{3,4}=0}$$

$$f_1=\frac{(e_{1,2}-e_{2a})}{Z_{2a}}=\frac{e_{1,2}-(f_1+f_4)G}{Z_{2a}}=\frac{e_{1,2}-f_1G-f_4G}{Z_{2a}} \tag{6}$$

$$f_1\left(1+\frac{G}{Z_{2a}}\right)=\frac{e_{1,2}-f_4G}{Z_{2a}}. \tag{7}$$

Writing the other loop equation

$$f_4=-\frac{(f_1+f_4)G}{Z_{3a}}\rightarrow f_4\left(1+\frac{G}{Z_{3a}}\right)=\frac{-f_1G}{Z_{3a}}$$

$$f_4=-f_1\,\frac{G}{(Z_{3a}+G)}. \tag{8}$$

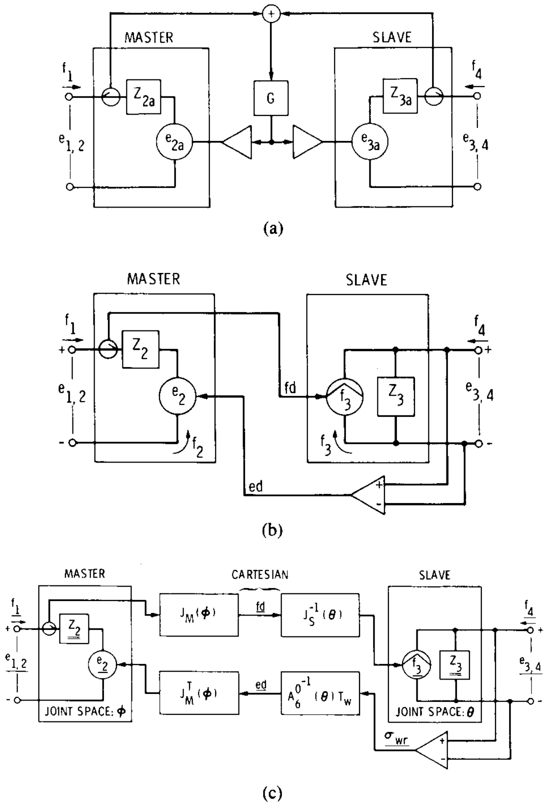

Fig. 2. Block diagrams of current teleoperator architectures. Force is sensed at the output port and sourced at the input. (a) "Classical" teleoperator in which torque commands to the master and slave are derived from position difference between them. (b) The "forward flow" system in which position is sensed at the input port and sourced at the output. Shown is a one-degree-of-freedom system, as used in [9]. (c) Six-degree-of-freedom "forward flow" system as in [6], [14].

Substituting into (7)

$$f_1\left(1+\frac{G}{Z_{2a}}\right)=\frac{e_{1,2}+\dfrac{f_1G^2}{(Z_{3a}+G)}}{Z_{2a}}$$

$$f_1\left(1+\frac{G}{Z_{2a}}-\frac{G^2}{Z_{2a}(Z_{3a}+G)}\right)=\frac{e_{1,2}}{Z_{2a}}$$

$$f_1=\frac{e_{1,2}}{Z_{2a}+G\left(1-\dfrac{G}{Z_{3a}+G}\right)}. \tag{9}$$

Thus from (6)

$$h_{11}=Z_{2a}+G\left(1-\frac{G}{Z_{3a}+G}\right). \tag{10}$$

The next parameter is the forward flow (velocity) transfer function h_{21}

$$h_{21}=\left.\frac{f_4}{f_1}\right\vert_{e_{3,4}=0} \tag{11}$$

$$f_4 = \frac{-(f_1 + f_4)G}{Z_{3a}} \tag{12}$$

$$f_4\left(1 + \frac{G}{Z_{3a}}\right) = -f_1 \frac{G}{Z_{3a}} \tag{13}$$

$$f_4 = \frac{-f_1 \dfrac{G}{Z_{3a}}}{\left(1 + \dfrac{G}{Z_{3a}}\right)} \tag{14}$$

$$h_{21} = \frac{-G}{(Z_{3a} + G)}\,. \tag{15}$$

Continuing to the second column of h, in which the input flow f_1 is set to zero

$$h_{12} = \left.\frac{e_{1,2}}{e_{3,4}}\right|_{f_1=0}\,. \tag{16}$$

Using (5)

$$h_{12} = \frac{f_1 G + f_4 G}{e_{3,4}} = \frac{f_4 G}{e_{3a} + f_4 Z_{3a}} \tag{17}$$

$$h_{12} = \frac{G}{G + Z3a} \tag{18}$$

and

$$h_{22} = \left.\frac{f_4}{e_{3,4}}\right|_{f_1=0} = \frac{f_4}{e_{3a} + f_4 Z_{3a}} \tag{19}$$

$$h_{22} = \frac{1}{G + Z_{3a}}\,. \tag{20}$$

The complete model is thus

$$h = \begin{bmatrix} Z_{2a} + G\left(1 - \dfrac{G}{Z_{3a} + G}\right) & \dfrac{G}{Z_{3a} + G} \\ \dfrac{-G}{Z_{3a} + G} & \dfrac{1}{Z_{3a} + G} \end{bmatrix}.$$

I now consider a recently used architecture in which force sensing is used at one port and position sensing at the other (Fig. 2(b)). This "Forward Flow" architecture has been implemented in the JPL FRHC-PUMA generalized bilateral teleoperator [6], [14]. It is interesting to point out that there is nothing about this architecture that mandates the designation of "forward" to the flow path. In fact, the master can be moved readily by human manipulation of the slave. This "forward effort" mode has been used in the JPL "force reflecting" trigger [15] in which finger force is sensed as the command to a gripper whose position is fed back through a lead screw drive mechanism.

Using the notation established in the figure, it is straightforward to calculate the h matrix for the basic forward flow architecture

$$h_{11} = \left.\frac{e_{1,2}}{f_1}\right|_{e_{3,4}=0} = Z_2 \tag{21}$$

$$h_{21} = \left.\frac{f_4}{f_1}\right|_{e_{3,4}=0} = -\frac{f_3}{f_1} = -1 \tag{22}$$

$$h_{12} = \left.\frac{e_{1,2}}{e_{3,4}}\right|_{f_1=0} = 1 \tag{23}$$

$$h_{22} = \left.\frac{f_4}{e_{3,4}}\right|_{f_1=0} = \frac{1}{Z_3}\,. \tag{24}$$

In comparing this model to the ideal system, note that the equivalent impedances Z_2 and Z_3 are typically a function of the controller gains as well as the mechanism impedances. Thus the system deviates from the ideal response only to the extent that the effects of the mechanism impedances are not entirely canceled by feedback control.

Extension to 6 DOF Case

To extend the above analysis to the case of a teleoperator with multiple mechanical degrees of freedom, there are two possible approaches. First, as in conventional master-slave teleoperators, the master and slave can be kinematically identical and multiple independent control systems can be connected between the corresponding joints. A future application of this concept will be the coupling of human exoskeletal controllers with anthropomorphic arms and hands.[1] In this case, many degrees of freedom will be coordinated by and redundancies will be resolved by the human nervous system. In nearer applications, the forward flow system can be expanded as in Fig. 2(c).

Each input flow (velocity) and effort (force) becomes a six-vector which is transformed to Cartesian coordinates through the appropriate transformations. Note that in the "forward flow" implementation, slave force is sensed at the wrist, first in terms of load cell strain σ_w which is transformed to wrist coordinates through the transformation T_w. Forces in wrist space are then transformed to Cartesian space by $A_6^{0^{-1}}(\theta)$, which is the transform from wrist to base coordinates. This force feedback is multiplied by $J_m^T(\phi)$, the Jacobian matrix transpose for the master, and then drives the master motors. Forward velocity commands are transformed into Cartesian space by $J_m(\phi)$ [16], and to slave joint space through $J_s^{-1}(\theta)$, the inverse of the slave Jacobian matrix. The mechanism impedances, Z_2 and Z_3, become matrices.

As in (21)–(24)

$$h_6 = \begin{bmatrix} Z_2(\phi) & J_m^T(\phi) A_6^{0^{-1}} T_w \\ J_m(\phi) J_s^{-1}(\theta) & Z_3^{-1}(\theta) \end{bmatrix}. \tag{25}$$

Problems due to conditioning in the neighborhood of singularities are revealed in the explicit formulation and their effects can be related to teleoperator fidelity through the hybrid parameters. Note that effort (force) feedback is not trans-

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[1] A. Bejczy, personal communication.

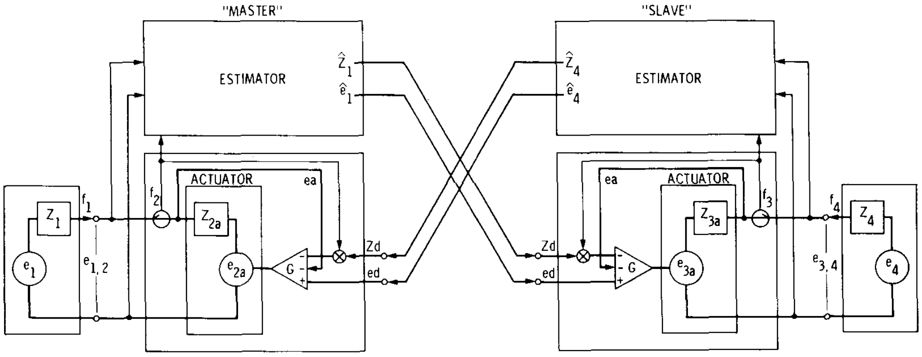

Fig. 3. Proposed generalized master–slave architecture: Bilateral Impedance Control.

formed by the slave Jacobian because it is never represented in joint space.

Derivation of H Matrix for an Advanced Teleoperator: Bilateral Impedance Control

Consideration of the Forward Flow teleoperator architecture raises some interesting questions. First, if the system can be operated in either direction, which direction, if any, is optimal? Second, although physically realized systems which implement the forward flow architecture tend to have very stiff mechanisms on the effort-sensing side, and compliant ones on the flow-sensing side, is there any basis for selecting these characteristics? Finally, although the forward flow architecture does come close to realizing the ideal response, the interaction between operator and environment which provides the kinesthetic sensation takes place via a "long loop" formed by the forward flow command and the returning effort feedback. Although this works well in current systems, recent simulation and experimentation [9] has shown that it is extremely sensitive to even small time delays.

As a result of these factors, a new, general architecture is proposed for teleoperators. This architecture (Fig. 3) features identical models for master and slave sides which can be fit to actual hardware by parameter variation. A local control law which enforces a desired impedance is implemented on each side. Each side of the teleoperator consists of a general machine built around an actuator with effort source e_{ia} (where i indicates the machine number and a stands for "actuator") and series mechanical impedance Z_{ia}. Each machine's controller implements the impedance law and thus has two inputs e_{id} and Z_{id}. The combined properties of the mechanism and control law thus yield effective efforts and impedances e_i and Z_i. The actuator effort e_{ia} is given by the control law

$$e_{ia}=G(e_{id}-e_{\text{out}}-Z_{id}f_{\text{out}}). \tag{26}$$

For example, in the case of the slave actuator, designated by the subscript 3,

$$e_{3a}=G(e_{3d}-e_{3,4}-Z_{3d}f_3) \tag{27}$$

where G is a controller gain which may be frequency-dependent.

In addition to the machines which energetically interact with the operator and environment, we require estimators which measure properties of the operator and environment. The variables which must be identified are $\hat{e}_i$ and $\hat{Z}_i$, $i=\{1, 4\}$ which are the efforts and impedances of the operator and environment. In addition to assuming that they exist (see discussion), we make the following assumptions:

1) The impedance estimators are implemented such that

$$e_{1,2}=0 \Rightarrow \begin{cases} \hat{e}_1=0 \\ \hat{Z}_1=0 \end{cases}$$

$$e_{3,4}=0 \Rightarrow \begin{cases} \hat{e}_4=0 \\ \hat{Z}_4=0 \end{cases}$$

and

2)

$$f_1=0 \Rightarrow \begin{cases} \hat{e}_1=e_{1,2} \\ \hat{Z}_1=Z_{\max} \end{cases}$$

$$f_4=0 \Rightarrow \begin{cases} \hat{e}_4=e_{3,4} \\ \hat{Z}_4=Z_{\max} \end{cases}$$

where $Z_{\max}$ is the value of the largest representable impedance.

Before computing the h parameters directly, a few intermediate results are obtained. First, we compute the effective Thevenin output impedance of the slave Z_3.

$$Z_3=\frac{\partial e_{3,4}}{\partial f_4} \tag{28}$$

$$e_{3,4}=e_{3a}+f_4Z_{3a} \tag{29}$$

$$e_{3,4}=G(e_{3d}-e_{3,4}-Z_{3d}f_3)+f_4Z_{3a} \tag{30}$$

$$e_{3,4}=\frac{Ge_{3d}+GZ_{3d}f_4+f_4Z_{3a}}{1+G}. \tag{31}$$

Therefore

$$Z_3=\frac{\partial e_{3,4}}{\partial f_4}=\frac{GZ_{3d}+Z_{3a}}{1+G}=\frac{G}{1+G}\left(Z_{3d}+\frac{Z_{3a}}{G}\right). \tag{32}$$

With similar derivations, one can obtain,

$$e_3=\left(\frac{G}{1+G}\right)e_{3d}\bigg|_{f_3=0} \tag{33}$$

and

$$f_3 = \left.\frac{G\hat{e}_1}{(Z_{3a} + G\hat{Z}_1)}\right|_{e_{3,4}=0}. \tag{34}$$

Note that because of the symmetrical architecture, the same results apply to Z_2, the master Thevenin impedance, e_2 the master effort (torque), and f_2, the master flow (velocity). The h parameters can now be calculated as follows:

$$h_{11} = \left.\frac{e_{1,2}}{f_1}\right|_{e_{3,4}=0} = Z_2 = \frac{G}{1+G}\left(Z_{2d} + \frac{Z_{2a}}{G}\right). \tag{35}$$

Using assumption 1

$$h_{11} = \frac{Z_{2a}}{1+G} \tag{36}$$

and

$$h_{12} = \left.\frac{e_{1,2}}{e_{3,4}}\right|_{f_1=0} = \frac{e_2}{e_{3,4}} = \frac{\frac{G}{1+G}\hat{e}_4}{e_4 + f_4 Z_4}. \tag{37}$$

From assumption 2 and (32) and (33), we have

$$\hat{e}_1 = e_{1,2}$$

$$e_3 = \frac{G}{1+G}\hat{e}_1$$

$$Z_3 = \frac{G}{1+G}\left(Z_{\max} + \frac{Z_{3a}}{G}\right).$$

Assuming $Z_{\max}$ is large, then $f_3 = f_4 = 0$

$$h_{12} = \left(\frac{G}{1+G}\right)\frac{\hat{e}_4}{e_4}. \tag{38}$$

Continuing to the second row

$$h_{22} = \left.\frac{f_4}{e_{3,4}}\right|_{f_1=0} = \frac{1}{Z_3} = \frac{1}{\frac{G}{1+G}\left(Z_{\max} + \frac{Z_{3a}}{G}\right)} \tag{39}$$

noting that $Z_{3d} = \hat{Z}_1$. Now

$$h_{21} = \left.\frac{f_4}{f_1}\right|_{e_{3,4}=0} = -\frac{f_3}{f_1} \tag{40}$$

$$\begin{aligned} &= -\frac{\frac{e_3}{Z_3}}{\frac{e_1 - e_2}{Z_1 + Z_2}} \\ &= -\frac{\frac{\hat{e}_1}{\hat{Z}_1 + \frac{Z_{3a}}{G}}}{\frac{e_1}{Z_1 + \frac{Z_{2a}}{1+G}}} \\ &= -\frac{\hat{e}_1\left(Z_1 + \frac{Z_{2a}}{1+G}\right)}{e_1\left(\hat{Z}_1 + \frac{Z_{3a}}{G}\right)}. \end{aligned} \tag{41}$$

We now have the complete h matrix in terms of the actuator impedances, gains, and estimator transfer functions

$$h = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$h = \begin{bmatrix} \dfrac{Z_{2a}}{1+G} & \left(\dfrac{G}{1+G}\right)\dfrac{\hat{e}_4}{e_4} \\ -\dfrac{\hat{e}_1\left(Z_1 + \frac{Z_{2a}}{1+G}\right)}{e_1\left(\hat{Z}_1 + \frac{Z_{3a}}{G}\right)} & \dfrac{1}{\frac{G}{1+G}\left(Z_{\max} + \frac{Z_{3a}}{G}\right)} \end{bmatrix}. \tag{42}$$

Thus as the estimates approach their actual quantities, e.g., $\hat{e}_1 \rightarrow e_1$, for small values of the actuator-impedance-to-gain ratios, and, in the case of h_{22} assuming $Z_{\max}$ is large, we have

$$h \rightarrow \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}. \tag{43}$$

SPICE Model of Bilateral Teleoperation

Simulation is a valuable tool to provide a bridge between theoretical ideas and the physical system. I have chosen to simulate bilateral teleoperation by transforming the system to an equivalent electrical network and simulating that network using SPICE, the circuit simulation system from the University of California, Berkeley [17]. Although there are several possible mappings from mechanical to electrical systems, effort (force) to voltage and flow (velocity) to current has several advantages [9] and was used throughout. Each component of the h matrix is a complex function of frequency. With the SPICE simulation, the frequency dependence of the h matrix can be calculated by using the built-in AC analysis function of SPICE. The AC analysis applies a sinusoidal signal to one of the independent variables (a voltage or current source), and observes the magnitude and phase of one of the dependent variables.

The SPICE model consists of a set of files containing SPICE input "cards" describing each of the main components of the system: the human operator, the hand controller, the communication channel, the manipulator, and the environment. For reasons of space, the SPICE model is not included here, but a full circuit diagram and input deck are given in [18].

When assembled together in a matrix (Fig. 4), the Bode plots representing the h parameters completely describe the frequency dependence of the teleoperator. Each describes a measurable quantity characteristic of the system's mechanical properties.

h_{11}, the input impedance (Fig. 4, upper left) is relatively flat out to about 30 Hz, but then shows strong frequency dependencies. Experimenting with variations of model parameters showed that the resonant peak at about 60 Hz was due to the natural frequency of the hand controller cable/handle system.

h_{12}, the reverse force gain (Fig. 4, upper right) shows flat

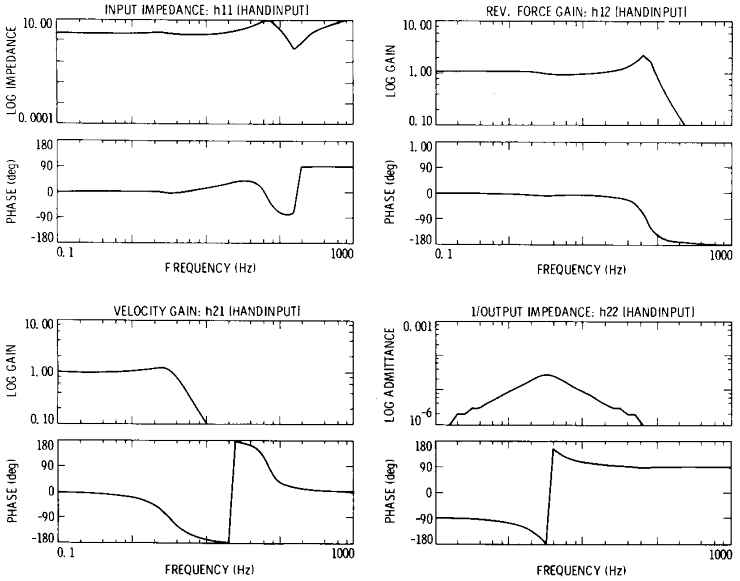

Fig. 4. Frequency-dependent h matrix computed with the SPICE model of an existing, one-degree-of-freedom, bilateral manipulation system. Note: phase angle of velocity gain h_{21} is shifted by artifact in SPICE algorithm for complex to polar conversion.

behavior out to about 80 Hz, but then drops sharply for higher frequencies. This effect is also due to the hand controller cable drive.

h_{21}, the velocity gain (Fig. 4, lower left) rolls off at a much lower frequency, beginning at about 3 Hz. This is, of course, limited by the manipulator (slave) dynamics.

h_{22}, the inverse of the output impedance (Fig. 4, lower right) shows a peak at the manipulator resonant frequency. Recall that the ideal h_{22} is zero, i.e., infinite output impedance (measured with zero input velocity). The peak at 3 Hz represents the manipulator's ability to absorb energy at it's resonant frequency.

The frequency-dependent h parameters thus illustrate how dynamic properties of the master and slave mechanisms affect teleoperator performance. With a suitable model and simulation the designer can thus observe the effects of mechanism parameters such as inertia and compliance on teleoperator performance. For example, the simulation indicates that force frequency response to the operator can be extended by attention to the dynamics of the hand controller cable drive.

DISCUSSION

Two-Port Hybrid Model of Teleoperation

A new model of teleoperators has been described which explicitly takes into account the bilateral exchange of energy between the operator and input port, and between the manipulator and environment. This model has the advantage of the simplicity of a linear model but is restricted in scope to operation about a given master and slave operating point. However, because it provides an intuitive representation of ideal teleoperator performance, it can be used to quanify degradation or enhancement of fidelity as a function of the configuration of the master and slave.

In an actual system, the two-port hybrid parameters can be measured in terms of input/output properties of the master and slave under specified boundary conditions (see Table I). This allows for the performance evaluation of actual hardware/control/software systems independent of the operator and environment. Results of these well-defined tests can then be compared with theoretical and simulation-based results in a consistent manner.

An important issue in teleoperator design is how to handle bilateral control in the region of singularities of the master and slave. For manipulation-critical tasks, some method of creating an "exclusion zone" around singularities must designed. Using the two-port hybrid model, effects of proximity to master and slave singularities can be quantified in terms of teleoperator performance. Thus an optimum tradeoff between teleoperation fidelity and reduced manipulation volume can be arrived at analytically.

The choice of one of the 6 two-port models induces an asymmetry or bias because of the relationship between the imposed boundary conditions and the control law used. For example, all of the hybrid parameters are defined in one of the two boundary conditions: input velocity = 0, or output force = 0. Because of this the performance of the Z_4 estimator does not appear in the hybrid model. The example initially assumes symmetry between master and slave sides, so that the dependence on performance of the impedance estimator is contained in h_{21}. This points out the asymmetry in the definition of the h parameters. Similar asymmetries exist in the other representations. In general, the representations have advantages and disadvantages which vary with the system under study.

The 6 possible matrix representations for two-ports arise from the 6 ways to choose two independent variables from four variables. Of these, the impedance (Z), admittance (Y), and hybrid (H) parameters are the most commonly used. As detailed in Chua *et al.* [4] all six are projections of the matrix equation

$$ME + NF = 0 \tag{44}$$

where M and N are 2×2 matrices of functions of s, and E and F are vectors representing efforts and flows at the ports.

The extension of the two-port model to the multi-DOF case (25) corresponds to the multi-port hybrid model. In the case of a 6-DOF bilateral manipulation system, each element of h_6 is a 6×6 matrix. The multi-port h matrix relates a vector of input velocities and output forces to output velocities and input forces. For traditional master–slave teleoperators in which the master and slave are kinematically identical, the submatrices of h_6 are diagonal and the system reduces to 6 independent two-ports.

SPICE Model of a Teleoperator

One benefit of computer simulation based on analytical models is that a quantitative prediction can be made from the model which can be directly compared with experimentally measured quantities. In this case, SPICE has been used to calculate the h matrix for a detailed model of a single-axis teleoperator testbed. Each element of the h matrix is a complex function of frequency which can be represented as a Bode plot (Fig. 4). Work is currently underway to make comparable measurements on the actual system. SPICE has proven to be a useful tool in this case because it can perform a flexible dynamic simulation of large networks.

The fair amount of effort involved in translating an electromechanical–physiciological system such as a teleoperator to a network of simple electrical components could be reduced if a program similar to SPICE having a wider repertoire of circuit elements was developed. In addition to the electrical circuit elements, mechanical elements, such as inertias and springs, and system elements such as summers, integrators, and amplifiers should be supported in a single integrated program. Each node's effort and flow would be either force/velocity or voltage/current. Transducers would link the mechanical and electrical systems. Such a simulation system would preserve the power and generality of SPICE but expand its applicability to a broader domain.

Nonlinearities

The two-port representation of a network is based on the concept of superposition, i.e., linearity. How useful is it for the nonlinear, configuration-dependent world of robot manipulators? The answer is that the two-port model characterizes teleoperator performance *around a given operating point.* The h parameters thus are derived from the second term of a Taylor series expansion describing the system [1].

In electronics, one of the most widespread uses of the hybrid two-port parameters, is to characterize bipolar transistors—highly nonlinear devices. In the case of transistors, the h parameters are defined in terms of changes around an operating point which forward biases the transistor. With a master–slave teleoperator, the operating point is a position and velocity for the master and slave. The position affects parameter values describing master and slave models, and the velocity offset can usually be ignored since manipulation usually takes place at a fixed worksite in the environment. The two-port hybrid parameter representation of the teleoperator thus can be a useful tool for understanding the configuration dependencies in manipulation because by calculating the frequency-dependent h parameters at a given operating point, manipulation fidelity can be estimated for that position, and its suitability for the task can be assessed.

The specification of the operating point around which the h parameters are estimated or calculated addresses the problem of configuration dependencies. Another commonly encountered nonlinearity is the discontinuous environment as found in the case of contact between the slave manipulator and a rigid environment. In this case, there is no meaningful linear approximation around the point of contact. Thus although the two-port model is useful to compute the separate responses of the system during free motion and full contact, the behavior during the contact transition can not be derived from the two-port (although much can be learned from the SPICE simulation) [9].

Bilateral Impedance Control

Bilateral impedance control has been shown to achieve good teleoperator fidelity under reasonable assumptions. It is also claimed that this control method can be applied to the problem of bilateral teleoperation under time delay. Existing architectures such as that shown in Fig. 1 and investigated in [9], [6] cannot handle even small time delays because transmission of impedance information occurs as efforts and flows are iterated around the complete control loop including the time delay. Bilateral Impedance Control suggests an alternative architecture (Fig. 3) in which a *local* servo loop enforces a commanded effort (force) and impedance. The information communicated across the time delay can be appropriately filtered to stabilize the system. In the steady state this will provide accurate operator perception of environmental characteristics, and present the environment with a suitable, operator-selected, impedance. However, frequency compensation (filtering) of this information to provide stability will degrade fidelity (as revealed in the h matrix). To the extent possible, this high-pass information about environmental impedance can be restored through a world model of the remote site—the topic of another paper. Because it combines open loop, high-frequency force information (from the world model) with low-pass feedback, this method is reminiscent of earlier work in robot force control [19].

Bilateral impedance control depends on the existence of an estimator which is capable of identifying the impedance of the environment and of the human operator. In general, this is a very difficult problem because of numerical conditioning problems and noise. Although ideal response ((26) and (27)) may be difficult to achieve in general, making assumptions about the environment can extend the usefulness of this approach. For example, the estimators can be assisted by an intelligent system with a reduced set of impedance vectors ($\hat{Z}_i$). The task of the estimator is then to classify the effort and flow sensor readings into one of the $\hat{Z}_i$. If the manipulation environment is man-made, the $\hat{Z}_i$ may correspond to known objects based on design properties.

In the case of the human operator estimator, the $\hat{Z}_i$ would correspond to predefined manipulation states, that is, levels of impedance corresponding to different manipulation subtasks. For example, fine position control (high mechanical impedance), free motion (medium), and force control (low). It would be desirable to identify these properties separately for different directions so that hybrid [20] control strategies can be transmitted to the slave.

CONCLUSIONS

Use of the two-port hybrid parameters for analysis of teleoperator systems has the following advantages:

1) The system is characterized in a compact and elegant fashion which retains the power of linear system representation while maintaining applicability to the nonlinear world of robot manipulators.

2) The two-port hybrid parameters are relatively easy to measure experimentally because they are derived from "black box" measurements at the input and output ports.

3) The h parameters provide a convenient means of characterizing the position and velocity dependencies of the teleoperator system in task-related terms. Thus effects of arm posture (master or slave) on manipulation can be computed easily and expressed compactly.

4) Ideal teleoperator performance is easily expressed, and actual performance can be easily compared between different teleoperators.

5) Required sampling rates in digital control implementations can be rationally determined by deriving bandwidth requirements from the h parameters.

6) A new teleoperator architecture, bilateral-impedance control, has been analyzed using the two-port hybrid model and is potentially useful for application with time delay. Use of the two-port model for analysis of the stability of this and other teleoperator architectures should be pursued.

ACKNOWLEDGMENT

The author would like to thank P. Fiorini, R. Anderson, and J. Raju for useful discussions.

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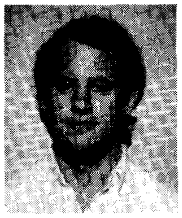

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