Stability and Transparency in Bilateral Teleoperation

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Abstract—Space applications of telerobots are characterized by significant communication delays between operator commands and resulting robot actions at a remote site. A high degree of telepresence is also desired to enable operators to safely conduct teleoperation tasks. This paper provides tools for quantifying teleoperation system performance and stability when communication delays are present. A general multivariable system architecture is utilized which includes all four types of data transmission between master and slave: force and velocity in both directions. It is shown that a proper use of all four channels is of critical importance in achieving high performance telepresence in the sense of accurate transmission of task impedances to the operator. It is also shown that transparency and robust stability (passivity) are conflicting design goals in teleoperation systems. The analysis is illustrated by comparing transparency and stability in two common architectures, as well as a recent “passivated” approach and a new “transparency optimized” architecture, using simplified one degree of freedom examples.

I. INTRODUCTION

TELEOPERATION has the potential to play a significant role in future space operations, such as the construction, servicing, and operation of remote platforms and vehicles. The advantages of remote manipulation over manned extravehicular activities (EVA) are clear: greatly reduced risk to personnel, reduced life support requirements and equipment, reduced logistics complexity due to continuous availability, and more efficient utilization of valuable human resources. These advantages will ultimately provide an overall increase in safety and a decrease in the cost of space operations. See [1] for a comprehensive overview of recent research and development in telerobotics for space applications.

However, current teleoperation systems are not capable of replacing an EVA astronaut in most manipulation tasks. Experience with current systems reveals a disappointing performance gap between direct manipulation, and operating the same task via a telerobot. For example, task completion times range from several times that of direct manipulation [2] up to two orders of magnitude larger [3], depending on the difficulty of the manipulation task. Much harder to quantify is the degree of telepresence, or the “feel” of the remote site available to the operator through the teleoperator device. Even the best current systems have a characteristically “mushy” feel, and extensive amounts of training are necessary to operate them safely and efficiently. In addition, significant communication delays are expected in space operations, from the smaller delays due to signal propagation over large distances, to the larger delays introduced by signal relaying, multiplexing, and coding/decoding. At some large delay, direct telemanipulation becomes impossible. Thus, the desire to utilize the unparalleled manipulation capability of a human operator must be balanced against the limits of technology in providing telepresence performance. To determine the role of direct (bilateral) teleoperation in space operations, e.g., to decide at what point communication delay becomes prohibitive, the limits of performance in the presence of delay must be more fully understood. Unfortunately, existing performance evaluations (e.g., [2]) have been carried out on teleoperation systems which do not provide optimal performance, hence the resulting judgements on the effects of communication delay may be premature. This paper presents an architecture which can provide optimal telepresence performance, and investigates the effects of communication delay in that context.

Until very recently, designs for teleoperation systems have focussed on static capabilities and kinematics, e.g., degrees of freedom, size of workspace, force/torque capability, etc., [3]. Although inertia and damping effects are often considered, this is usually from an energy efficiency viewpoint, where the desire is to minimize the effort needed to accomplish the teleoperation task, or to reduce coupling between motion axes. Even the design of teleoperator control architectures has been primarily motivated by static performance considerations.

Consider the position–position architecture [4], where master position is passed as a command to the slave servo (position) controller, and slave position is returned to the master as a position command. This makes sense if the position controllers have good tracking capabilities, since the master and slave will closely follow each other. However, master and slave are interconnected in a feedback loop, and the dynamics of the closed loop system must also be considered. For example, in this position–position architecture it has been observed that a highly accurate position control system on the master is not desirable. This makes the system feel “sluggish” in free space motion, since the lags between master and slave position movements cause large reaction forces to be supplied to the operator.

In the position–force architecture [5], the idea is also to send master positions as commands for the slave to follow. But the interaction force at the slave is sent back directly as a reaction force to the master. If the slave faithfully reproduces the master motions, and the master accurately feels the slave forces, the operator should experience the same interaction with the teleoperated task as would the slave. Again, this static way of thinking does not address the dynamics of the interconnected system. In this force reflection architecture,
stability is often a problem unless the force feed back to the master is significantly attenuated.

Recent work in bilateral teleoperation has focussed more on dynamics and stability, and has lead to a variety of proposed architectures. Passivity theory is the basis for the modifications of basic position–position and position–force architectures discussed in [6] and [7], [8], respectively, to deal with communication delays. Robust control ideas based on small gain theory motivate the force–force architecture [9], and passivity is the basis of the work in [10], although communication delays are not considered. [11] is based on Lyapunov stability theory, which cannot address the infinite-dimensional models generated by communication delays. Transparency performance of these overall teleoperator systems are not addressed.

Other work has concentrated on performance—objectives for architecture design based on specifying network theory hybrid parameters are discussed in [12]; the network hybrid parameter design problem in [13] is phrased in terms of a transparency objective, and suggests a position–position approach. Unfortunately, infinite gains are required for accurate transparency. General architectures quite similar to that discussed here were developed independently in [14] and [15]. Stability and transparency are also treated in [14], but only in the zero communication delay case. Transparency of the overall system is not addressed in [15].

In this paper, the trade-off between stability and performance is explicitly addressed in the presence of communication delays. The limits of telepresence performance are explored using the concrete notion of transparency (see Section II). When applied to a general teleoperation architecture introduced in Section III, this notion of transparency leads to specific guidelines for improving teleoperation performance (see Section IV). Since stability is often the limiting factor in improving performance, a general analysis approach based on passivity ideas is discussed in Section V. These stability results extend those of [7], [6] to allow the destabilizing effects of communication delay to be reduced in any teleoperation architecture. Section VI contains a detailed comparison of the "passivated" position–position and position–force types of teleoperator systems, as well as the approach of [7], and a new "transparency optimized" architecture, which is similar to [14], but augmented with "passivation" for delayed communication links.

II. TRANSPARENCY AS A PERFORMANCE MEASURE

In any bilateral teleoperator system design, the essential desire is to provide a faithful transmission of signals (positions, velocities, forces) between master and slave to couple the operator as closely as possible to the remote task. Ideally, the teleoperation system would be completely transparent, so operators feel that they are directly interacting with the remote task [13]. Note that when in contact with the task, the slave velocities $V_s$ and forces $F_s$ are not independent. They are related by the impedance $Z_s$ of the task (slave environment).

$$ F_s = Z_s(V_s) $$

If operators are to feel as if they are touching the task directly, then the operator's force on the master $F_h$ and the master's motion $V_h$ should have the same relationship, i.e., for the same forces $F_s = F_h$ we want the same motions $V_s = V_h$. This requires that the impedance $Z_t$ transmitted to or "felt" by the operator, defined by $F_h = Z_t(V_h)$, satisfies the transparency condition

$$ Z_t = Z_s. $$

In practice, perfectly transparent teleoperation will not be possible. So it makes sense to ask the following questions:

- What degree of transparency is necessary to accomplish a given set of teleoperation tasks?
- What degree of transparency is possible?
- What are suitable teleoperator architectures and control laws for achieving necessary or optimal transparency?

We focus on the second two questions in this paper. Instead of evaluating the performance of a specific teleoperation architecture, as in [2], we seek to understand the fundamental limits of performance and design trade-offs of bilateral teleoperation in general, without the constraints of a preconceived architecture.

Fig. 1 is a model of a teleoperation system in its most general form. The task impedance $Z_t$ is transmitted to the operator through the teleoperation system $T$, which is a two port relating slave forces and velocities to master forces and velocities. The impedance of the operator's hand is given by $Z_h$. The impedance $Z_t$ transmitted to the operator is then a function of the task impedance $Z_h$. The form of this function characterizes the transparency of the teleoperator system, hence transparency is a function only of the teleoperator system, not of the task impedance $Z_t$ nor of the hand impedance $Z_h$. In general, the two port is "smooth" enough that its behavior can be accurately described by a linear model in the neighborhood of a given operating point, e.g., at a point of contact with the teleoperation task.

However, a well-defined transparency function will only exist if the entire teleoperation system, including task and human operator, is stable. The dynamics of the teleoperator can cause annoying and unsafe contact "bounce," especially when communications delays are large. While the effects of such instability are amplified by the nonlinear transition between contact and free space motion, the source of this instability can be traced to unstable or poorly damped linear dynamics while in contact. A necessary condition for good overall transparency
is therefore that the linearized behavior of the system (e.g., while maintaining contact with the task) has desirable stability and transparency properties. In this paper, we concentrate on this linearized behavior. This allows the entire system to be characterized in the frequency domain using Laplace transforms. For the teleoperator two-port, we have the general hybrid matrix formulation [12], [13], [16]

\[
\begin{bmatrix}
F_h(s) \\
V_h(s)
\end{bmatrix} =
\begin{bmatrix}
H_{11}(s) & H_{12}(s) \\
H_{21}(s) & H_{22}(s)
\end{bmatrix}
\begin{bmatrix}
V_e \\
-F_e
\end{bmatrix}.
\]

Solving for \( F_h \) and \( V_h \) in terms of \( V_e \) and \( F_e \), using the task impedance \( F_e = Z_t V_e(s) \), and eliminating \( V_e \) yields the transmitted impedance (dropping the Laplace \( s \) for clarity)

\[
F_h = \left( H_{11} - H_{12} Z_t \right) \left( H_{21} - H_{22} Z_t \right)^{-1} V_h.
\]

Although this expression can become very complicated if the \( H_{ij} \) have significant dynamics, there are some fundamental insights to be derived from (4):

a) Perfect transparency \( (Z_t \equiv Z_e) \) requires that \( H_{22} = 0 \), \( H_{21} Z_t = Z_t (H_{12}), \) and \( H_{11} = 0 \).

b) As \( Z_t \rightarrow 0 \), the transmitted impedance is insensitive to \( Z_t \) if \( H_{11} \neq 0 \), which requires that \( H_{11} \neq 0 \). If \( H_{11} \neq 0 \), and \( H_{12} \neq 0 \), and \( H_{22} \neq 0 \), and \( H_{21} \neq 0 \), then 

\[
H_{11} Z_t \rightarrow \infty,
\]

c) As \( Z_t \rightarrow \infty \), the transmitted impedance becomes \( H_{12} H_{22}^{-1} \), which is insensitive to \( Z_t \).

Each of the \( H_{ij} \) parameters is potentially affected by the mechanical dynamics of the master and slave, as well as by the control architecture. Thus it is not possible to arbitrarily select the hybrid parameters, say to satisfy the item a) above. The alternative is to examine how practical limitations affect the ability of the teleoperator system to transmit the task impedance to the operator. To do this, some structure must be imposed on the teleoperator architecture. The next section examines a general control architecture, and develops a corresponding expression for the achievable impedance \( Z_t \).}

### III. A GENERAL TELEOPERATOR ARCHITECTURE

A bilateral teleoperator system consists of the master and slave mechanical systems, often with some degree of "self control," i.e., control loops closed separately around master and slave. For example, in the position-position architecture, master and slave each have position control loops to enable tracking of position commands. Other control loops are constructed by establishing communication links between master and slave. In general, both positions and forces can be communicated bilaterally, as well as various filtered versions of positions and forces. Fig. 2 shows a block diagram of the entire teleoperation system, including master, slave, bilateral communication, operator, and task (environment) dynamics. This architecture represents all teleoperation structures to appear, by suitable specialization of the subsystem dynamics.

The external forces \( F_e \) and \( F_h \) are independent of teleoperator system behavior. The nomenclature of the subsystem blocks is listed in Fig. 3, together with the typical values of various blocks for the two most common teleoperator architectures. Other more recent architectures are also captured by the general structure of Fig. 2. For example, [13] has a generalized position-force form, and [16] discuss modified position-force strategies, and [17] proposes a force-force architecture. Other structures utilizing all four communication paths \( C_1, C_2, C_3, C_4 \) have also been suggested [14], [15].

Arguments have been made for preferring one architecture over another, e.g., using notions of operator information capacity [18]. And operator performance studies using various specific architectures have been carried out [2], [16]. Although this type of functional information is of great importance to users, it is difficult to correlate to specific design choices and unambiguous measurements of teleoperator system properties needed by system designers. In this paper, the general architecture of Fig. 2 is used to analyze and quantitatively compare various teleoperation schemes in terms of transparency, performance, and stability. This systematic approach reveals that all four information channels between master and slave are necessary to achieve good transparency. It is also shown that transparency and robust stability (passivity) are conflicting objectives, and a trade-off must be made in practical applications.

Fig. 3 provides a simplified description of the subsystem blocks in the general architecture of Fig. 2. These typical forms for subsystem dynamics are intended to capture only the dominant effects, and will be used as concrete examples to accompany the analysis results. More complex descriptions of the blocks in Fig. 2 can be used to provide more realistic measures of teleoperation performance as needed for a given application. The stability and transparency analyses discussed in this paper are quite general, however, and do not depend on the simplified forms for the components listed in Fig. 3. Note that velocities are used in all dynamic descriptions in this paper rather than positions. Stability and transparency are unaffected by this convention, although communicating
velocities rather than positions can lead to small offsets between master and slave positions. Since position indexing is common in bilateral teleoperation (to overcome workspace limitations of the master), and visual feedback is relied upon, this presents no difficulty. If transitions from teleoperated to autonomous operation are desired, initial positions can be communicated between controllers to obtain the desired absolute position registration.

Solving for the transfer functions between master and slave forces and velocities in (3) yields the following expressions for the hybrid parameters in terms of the subsystems in Fig. 2.

\[
\begin{align*}
H_{11} &= (Z_m + C_m)D(Z_s + C_s - C_3C_4) + C_4 \\
H_{12} &= -(Z_m + C_m)D(I-C_3C_2) - C_2 \\
H_{21} &= D(Z_s + C_s - C_3C_4) \\
H_{22} &= -D(I-C_3C_2)
\end{align*}
\]  

where \( D = (C_1 + C_3Z_m + C_3C_m)^{-1} \). These expressions can be used to design a desired set of \( H \) parameters by choice of suitable control laws \( C_1, C_2, C_3, C_4, C_s, \) and \( C_m \). Using (5)-(8) in (4), a general expression for the transparency can be obtained. This expression can be used to quantitatively compare the transparency performance of competing teleoperation architectures (see Section VI). It can also be used as a design tool to improve or optimize transparency, as shown below.

### IV. OPTIMIZING FOR TRANSPARENCY

The general expression for transmitted impedance provides the essential constraints on the design of a teleoperator architecture which is optimized for transparency. Ideally, we would like to have complete transparency, i.e., \( Z_t = Z_r \) over all frequencies. From (4) and (8), this would suggest setting

\[
C_3C_2 = I
\]

(9)

to remove \( Z_r \) from the denominator of (4). Then if we also set

\[
C_4 = -(Z_m + C_m) \quad \Rightarrow \quad C_1 = (Z_s + C_s)
\]

(10)

the \( H_{11} \) term in the numerator of (4) will vanish, making \( Z_t \) a linear function of \( Z_r \):  

\[
Z_t = -H_{12}Z_rH_{21}^{-1} = C_2Z_r.
\]

(11)

This suggests that when \( C_2 = I \), complete transparency is obtained. In some applications, a more general type of transparency (telefunctioning [9]) may be desired, e.g., to have "uniform" transparency over the frequency spectrum, but have a nonunity scale factor. In remote operation of heavy machinery or construction robots, a \( C_2 \) smaller than unity might be desired to reduce operator fatigue. In teleoperation of micromachines, e.g., in microfabrication or microsurgery, a \( C_2 \) larger than unity may be required so that impedances can be scaled up to human levels of sensitivity.

Unfortunately, the control laws (10) for \( C_1 \) and \( C_4 \) require acceleration measurements since \( Z_m \) and \( Z_t \) contain \( s \) terms due to the inertial part of the impedance (refer to Fig. 3). If good transparency is required over a large frequency bandwidth, the additional complexity of adding accelerometers and requiring accurate knowledge of inertial parameters may be justified (see the work of [14]). However, good low frequency transparency can be obtained using simpler control laws which only require position and velocity measurements to implement \( C_1 \) and \( C_4 \). Consider the following simplified control laws

\[
C_1 = \dot{Z}_s + C_s \quad C_4 = -(\dot{Z}_m + C_m)
\]

(12)

where the "hat" impedances contain only those terms in the form \( As^i, i \leq 0 \). At low frequencies, the transparency (11) is then obtained. At higher frequencies, the value of \( Z_t \) becomes increasingly inaccurate as a representation of the environmental impedance \( Z_r \). The transparency performance of such a simplified scheme can be precisely evaluated by substituting the actual values for the control laws into the expressions (5) through (8), and computing \( Z_t \) via (4). In general, it would be desired to obtain good transparency at low frequencies, so the operator can accurately determine stiffnesses while in contact with a rigid task, or determine payload inertias while in free space motion. The higher the bandwidth of this accurate transparency, the larger the degree of telepresence, although quantitative measures of desired bandwidths have yet to be determined for transparency. Eventually, stability becomes a limiting factor in achievable bandwidths, as discussed below.

The key to achieving the high levels of transparency in (11) and the simplified approach via (12) is the removal of the \( H_{11} \) and \( H_{22} \) terms from (4). This, in turn, requires the use of all four information channels in Fig. 2 (velocity and force channels in both directions). This architecture does not correspond to existing two-channel topologies [18]; it is truly a "four-channel bilateral architecture." In particular, the choice \( C_2C_3 = I \) is dictated by the transparency objective and the expressions (4) through (8) for the transmitted impedance.

The natural suspicion is that this "force feedforward" is necessary to provide quick response and better high frequency transparency. However, as shown in Section VI, this force information is also necessary for accurate low frequency transparency.

Since transparency performance is only measured by the values \( Z_t \) at various frequencies, nothing can be inferred about the stability of the teleoperation system. Indeed, \( Z_t \) in the expression (4) can appear to have a well behaved frequency response while the feedback connection of master and slave is unstable. In this case the expression for \( Z_t \)
is meaningless. To properly evaluate the transparency of a teleoperator architecture, stability conditions must be included in the design. This is the subject of the next section.

V. STABILITY ANALYSIS VIA PASSIVITY

The basic feedback structure of the teleoperator system of Fig. 2 can be seen more clearly by defining the intermediate variables $F_c$ and $F_{ch}$ in the following relationships between signals in Fig. 2:

\[ F_c = (Z_e + Z_t + C_4) V_e \]
\[ F_{ch} = (Z_m + Z_h + C_m) V_h \]

and rearranging the block diagram as in Fig. 4. A precise necessary and sufficient condition for stability is extremely difficult to obtain, since all paths in Fig. 4 are multivariable. However, a sufficient condition for stability based on passivity arguments is well-suited to this application, since the design of $C_1, C_2, C_3,$ and $C_4$ for good transparency usually implies strong coupling from master to slave (large loop gains in Fig. 4). In contrast, the sufficient conditions for stability resulting from small gain arguments will only be satisfied in special circumstances (e.g., when the environment is softer than the teleoperator system as required in [9]). In general, this approach would result in conservative design criteria (leading to poor transparency), hence is not considered here.

More formally, an application of the "passivity theorem" [19] to the system in Fig. 4 provides the following result.

**Theorem I:** Let $S_1 = (C_4 + C_2 Z_c) (Z_e + Z_t + C_4)^{-1} (C_1 - C_3 Z_h)$ and $S_2 = (Z_m + Z_h + C_m)^{-1} (C_1 - C_3 Z_h)$. Then bounded inputs $F^*_c$ and $F^*_h$ imply all teleoperator signals are bounded provided the following conditions hold:

1a) $S_1$ is a strictly positive real transfer function (exponentially stable, and $S_1(j\omega) + S_1^T(-j\omega)$ uniformly positive definite over all frequencies $\omega$).

1b) $S_2$ is a positive real transfer function ($S_2(j\omega) + S_2^T(-j\omega)$ positive semi-definite over all $\omega$).

1c) The transfer functions $(C_1 + C_2 Z_c) (Z_e + Z_t + C_4)^{-1}$, $(Z_m + Z_h + C_m)^{-1}$, and $(C_1 - C_3 Z_h) (Z_m + Z_h + C_m)^{-1}$ are stable.

**Proof:** The conditions 1a) and 1b) imply that $S_1$ is strictly passive with finite gain, and $S_2$ is passive, satisfying the passivity theorem, hence the feedback system is $L^2$ stable [19]. E.g., $F_{ch}$ and $V_h$ in Fig. 4 are square integrable when $F^*_c - C_3 F^*_h$ is square integrable and $-F^*_h + C_3 F^*_h = 0$. Since the system is linear and time-invariant, $L^2$ stability implies BIBO stability. Condition 1c) ensures all other teleoperator signals are bounded.

Q.E.D.

**Remark:** The strict passivity (strictly positive real) condition on at least one subsystem in Theorem 1 is essential: Consider the case where $S_1 = S_2 = 1/s$. Both subsystems are passive, but neither is strictly passive nor do they have finite gain. The feedback connection of $S_1$ and $S_2$ has imaginary axis poles, and is not bounded-input bounded-output stable.

Unfortunately, if the signals communicated between master and slave are delayed, conditions 1a) and 1b) of Theorem 1 will not hold. This is easy to see in one degree of freedom case, where $C_1$ through $C_4$ are scalars multiplied by the delay operator $e^{-sT}$, where $T$ is the one-way delay in transmitting information between master and slave. Then $S_1$ contains a factor of $e^{-2sT}$, and cannot be strictly positive real (cannot have a real part bounded away from zero for all frequency). Therefore, simply adding delay to an otherwise passive teleoperator design destroys passivity, and with it the guarantee of stability. A related analysis appears in [14], where the teleoperator device is shown to be passive via scattering theory when communication delays are zero. But it can also be shown that this passivity is destroyed by any delay in the communication channel, no matter how small (the scattering operator singular values become larger than unity).

However, by suitable reformulation of the information transmitted, it is possible to retain passivity in the presence of communication delays. The development below was motivated by [7] where such a reformulation was used to modify a position–force teleoperator architecture. Since then, this idea has been applied to the position–position architecture [6]. The approach given here is more general, since it can be implemented on any teleoperator system in the form of Fig. 2. Also, the development is more elementary, and does not rely on electric circuit equivalents of teleoperator dynamics.

The essential idea is to associate the abstract notion of passivity (positive real transfer functions) to a more physical measure of passivity, i.e., one where the covariant (through and across) variables at a driving point (or port) in a system must be "in phase," so the net "energy" supplied to the system is positive. More specifically, if $T$ is a vector of through variables and $A$ is the corresponding vector of across variables, then the system is passive [7], [19] if

\[ \int_0^T T^T(\tau) A(\tau) d\tau \geq -S_0, \quad \forall t > 0 \]

where $S_0$ is a fixed number often associated with the initial stored energy at $t = 0$. The architectures [7], [6] are derived from this point of view where $T$ and $A$ are physical quantities (e.g., force and velocity). This leads to the transmission of specific linear combinations of master and slave forces and velocities between master and slave. As shown in Section VI, this degrades the transparency of the overall teleoperator.
system. Here, we allow other combinations of teleoperator signals to be transmitted, resulting in nonphysical through and across variables, but providing improved transparency and a passive communication link.

Consider the schematic representation of the teleoperator system as shown in Fig. 5. In this representation, the inputs to the communication link are the across source $A_1$ at the master, and the through source $T_2$ at the slave. These sources have a functional dependence on the velocities of master and slave, respectively. Outputs are the through variable $T_1$ at the master and the across variable $A_2$ at the slave. The force sources $F_{th}$ and $F_{sc}$, in turn, are related to these communication link outputs.

There are several possible relationships between communication link signals and teleoperator forces and velocities which preserve the teleoperator structure of Fig. 2. One such set of through and across source dependencies is

$$A_1 = (C_1 - C_2 Z_h) V_h + C_3 F_{th}^*$$

$$F_{th} = -T_1 + F_{th}^*$$

$$F_{sc} = -A_2 + F_{sc}^*$$

$$T_2 = (C_4 + C_2 Z_h) V_c + C_2 F_{sc}^*$$

which is easily seen to satisfy (13) and (14) in the absence of communication link delay. Other definitions are possible, but this one does not require knowledge of $Z_c$ and $Z_h$ for implementation (see the discussion on implementation following (34)). Note that when there is no delay in the communication link, we will want $T_2 = T_2$ and $A_2 = A_1$ to recover the original system of Fig. 4. (Source variables on the right side of the equalities produce the outputs on the left). Fig. 6 shows a block diagram of this arrangement in input/output form, where the transfer function matrix $N$ is given by

$$N = \begin{bmatrix} 0 & N_2 \\ N_3 & 0 \end{bmatrix}$$

where

$$N_2 = (C_4 + C_2 Z_h)(Z_m + Z_s + C_2)^{-1}$$

$$N_3 = (C_1 - C_3 Z_h)(Z_m + Z_h + C_m)^{-1}$$

The model for the communication link must be re-formulated to map across variables to through variables in accordance with (15). The form of $K$ is needed for implementation, however, and will be derived presently.

Observe that the communication link can be described by disconnecting it from the system, and "looking into" the ports at each end of the link, i.e., by examining the relationship between the signals ($T_1$, $A_1$) and ($T_2$, $A_2$). Similarly, the remaining portion of the disconnected system, including master, slave, environment, and human operator (which we define as the teleoperator portion) can be described by "looking into" the overall system at these same points of connection, or ports. The overall system can then be viewed as a connection of two two-ports $L$ and $P$ as defined below. Let $T^T = [T_1, -T_2]$, and $A^T = [A_1, A_2]$. Then the transfer function $L(s)$ defined by

$$T = L(s)A$$

$$A = P(s)(-T) = \begin{bmatrix} P_1 & 0 \\ 0 & P_4 \end{bmatrix}^{-1}$$

The model for the communication link is given by

$$N = \begin{bmatrix} 0 & N_2 \\ N_3 & 0 \end{bmatrix}$$

$$N_2 = (C_4 + C_2 Z_h)(Z_m + Z_s + C_2)^{-1}$$

$$N_3 = (C_1 - C_3 Z_h)(Z_m + Z_h + C_m)^{-1}$$

Fig. 6. Input/output block diagram of the teleoperator system based on the two-port representation of Fig. 5, using the source dependencies of (16)-(19).

Note that the operator $K$, which describes the communication link as a map from inputs ($T_1$ and $T_2$) to outputs $T_1$ and $A_2$, will not be passive, even in the absence of delay, i.e., with no delay.

$$K = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

The model for the communication link must be re-formulated to map across variables to through variables in accordance with (15). The form of $K$ is needed for implementation, however, and will be derived presently.
Then the teleoperator part of the system is passive if \( P(s) \) is a positive real transfer function. The overall teleoperator system can then be transformed into the through versus across form of Fig. 7. Applying the passivity theorem to Fig. 7, we have the following result.

**Theorem 2:** With bounded inputs \( F^o_h \) and \( F^r_e \), all signals in the overall teleoperator system, including the communication link, are bounded provided the following conditions hold.

1. \( P(s) \) is a positive real transfer function.
2. \( L(s) \) is a strictly positive real function.
3. The transfer functions \((C_4 + C_2 Z_r)(Z_s + Z_c + C_s)^{-1}\), \((Z_s + Z_c + C_s)^{-1}\), \((C_1 - C_3 Z_h)(Z_m + Z_r + C_m)^{-1}\), and \((Z_m + Z_r + C_m)^{-1}\) are stable.

**Proof:** Since \( P(s) \) may be nonproper, the conditions of the passivity theorem as stated in [19] do not hold. However, since all system signals are uniquely defined for any external inputs (the teleoperator system is an interconnection of causal linear systems), and \( P(s) \) is obtained by a causal loop transformation of Fig. 6, the manipulations of input-output inner products in the proof of the passivity theorem carry through. Thus, the additional conditions 2a) and 2b) are enough to prove that \( T_1, A_1, T_2, \) and \( A_2 \) are in \( L^2 \) when \( F^o_h = C_2 F^r_e \) and \( F^r_e + C_3 F^o_h \) are in \( L^2 \). Linearity, time-invariance, and condition 2c) imply that all system signals are bounded when inputs are bounded.

Hence, when \( P \) is positive real, all that is necessary for guaranteed stability in the presence of delay is that \( L \) is stable and strictly positive real. An example of such a passive delay operator is an electrical transmission line, which is the basis of the idea in [7]. Here we add a “loss factor” delay operator is an electrical transmission line, which is

which specifies a channel with one-way delay of \( T \), a wave attenuation factor of \( e^{-bT} \), and a low pass filtering effect with bandwidth \( a \) rad/s. From (21), solving (23) for \( T \) in terms of \( A \) results in

\[
T = \frac{1}{2} \ln \left( \frac{1 - e^{-2(\alpha + b)T} + \sqrt{(1 - e^{-2(\alpha + b)T})^2 - 4e^{-2\alpha T}}}{1 - e^{-2\alpha T}} \right)
\]

which has poles to the left of \( \min(a(e^{-\alpha T} - 1), -b + \epsilon) \) for arbitrarily small \( \epsilon > 0 \), hence is stable. It can also be verified that \( L(j\omega) + L^T(-j\omega) \) is uniformly positive definite over all \( \omega \), as required for strict passivity in Theorem 2. Since the algebra is tedious, we can appeal to the loop transformation theorem [19] which shows that \( L \) is strictly passive if \( \bar{S} \) has an induced euclidean norm less than one. This norm is given by the largest singular value of \( S(j\omega) \) over all frequency, or equivalently by

\[
\sup_{\omega} |S(j\omega)| \leq e^{-\alpha T} < 1.
\]

Thus Theorem 2 is satisfied by the form (25) for the communication link.

To implement this strictly passive communication link, rearrange (23) to obtain the transfer function \( K(s) \),

\[
\begin{bmatrix} T_1 \\ -A_2 \end{bmatrix} = K(s) \begin{bmatrix} T_2 \\ A_1 \end{bmatrix}.
\]

The result for \( K(s) \) is

\[
\begin{bmatrix} 2e^{-2(\alpha + b)T}/(1 + \alpha s/a)^2 \\ -2e^{-2(\alpha + b)T}/(1 + \alpha s/a)^2 \end{bmatrix}
\]

Using the source relationships (16) and (19), and noting that the definitions (13) and (14) imply

\[
F_{ch} = (Z_m + Z_h + C_m)V_h
\]

we can write the teleoperator system equations in the form

\[
(Z_m + Z_h)V_h = -C_m V_h - (C_4 + C_2 Z_r)e^{-aT} V_r
\]

\[
- C_3 e^{-bT} F_r + (I - H_2 C_2) F^o_h
\]

\[
(Z_s + Z_r)V_r = -C_1 V_r - (C_1 - C_3 Z_h)e^{-aT} V_h
\]

\[
+ C_0 e^{-bT} F_h - (I - H_2 C_2) F^e_r
\]

where the new control laws (the “primed” \( C \)’s) are related to the original control laws as follows. Define the filters

\[
H_1(s) = \frac{2e^{-bT}/(1 + s/a)}{1 + 2e^{-2(\alpha + b)T}/(1 + s/a)^2}
\]

\[
H_2(s) = \frac{1 - e^{-2(\alpha + b)T}/(1 + s/a)^2}{1 + 2e^{-2(\alpha + b)T}/(1 + s/a)^2}
\]

Then

\[
C_i' = H_1(s)C_i, \quad i = 1, 2, 3, 4
\]

\[
C_o' = C_o + H_2(s)(C_1 + C_3 Z_h)
\]

\[
C_m' = C_m + H_2(s)(C_1 - C_3 Z_h).
\]

Thus, the original control laws \( C_m \) and \( C_o \) on the master and
slave are augmented with terms that depend on the delay in the communication channel \((H_2(s))\), and terms which depend on the original (undelayed) control laws between master and slave \((C_1 \text{ through } C_4)\). The new (delayed) control laws which link master and slave are simply the undelayed ones, altered by the addition of the filter \(H_1(s)\).

It may appear that the environment and human impedances \(Z_e\) and \(Z_h\) are required to implement the modified control laws (34), (35). Actually, knowledge of these impedances is not necessary, since \(C_1\) operates on \(V_e\), hence the expression \(H_2(s)C_2Z_eV_e + H_2C_2Fh\) is available as a filtering on the measured environmental force: \(H_2(s)C_2F\). Similarly, the term involving \(Z_h\) in (34) is implemented by filtering the measured hand force \(F_h\) on the master.

The modified control elements (33)–(35) can be implemented in the teleoperator architecture using additional delay elements in the master and slave controllers as shown in Fig. 8. Alternatively, the added delays can be achieved by transmitting additional signals over the communication channel and back (two channel-delays are required). If a digital implementation is used, the required delays are easily obtained via software buffering of sampled data.

Although Theorem 2 provides only sufficient conditions for stability, it is useful because it is easily applied to multivariable systems. Recent research on “almost passive” systems [20] also promises to extend the application of these ideas. Even in cases where Theorem 2 cannot be used, the idea of using a passive communication link has merit, so at least the \(L\) in Fig. 7 does not “generate energy.” Although the addition of such an \(L\) can indeed destroy stability, contrary to the implication in [7] (unless \(P\) is also passive), this approach would seem a very benign way to accommodate communication delay. Including such an \(L\) provided improved stability in the simulation examples provided in Section VI, hence was included in every case for ease of comparison.

VI. A PERFORMANCE COMPARISON

Several common teleoperation architectures are quantitatively compared in this section, using the impedance \(Z_t\) reflected to the operator, passivity of \(P(s)\) from Fig. 7, and stability via Nyquist plots as measures of overall performance. The position–position [4], position–force [5], “passivated” position–force [7], and the new “transparency optimized” architectures will be examined. This comparison uses a simplified description of the multivariable system of Fig. 2, where only a single degree of freedom is modeled. To distinguish the scalar case, all operators from Fig. 2 will be written in lower case. This comparison does not include all possible operating scenarios, nor does it provide a comprehensive study of the effects of various time delays. But it does clearly show that trade-offs exist in satisfying both passivity (stability) and transparency criteria. In an actual application, the tools presented in Sections II, III, and V can be used to guide design modifications to achieve an acceptable trade-off between transparency performance and stability for a given master/slave, given time delay, etc.

Substituting the expressions (5)–(8) into (4) and simplifying yields the scalar transmitted impedance

\[
z_t = \frac{(z_m + c_m')z_a + c'_a c_m + z_e(z_m + c_m' c_a') + z_s[1 - c_m']}{z_s + c'_a z_a + z_s[1 - c_m']},
\]

Note that the “primed” control laws from Section V, equations (32)–(35), are used to guarantee a passive communication channel. In each of the following cases, the channel delay
and loss factors are as

\( T = 0.05 \text{ s} \quad b = 0.02 \quad a = 20 \text{ rad/s} \) (37)

The delay of 50 ms was chosen as a representative "median" delay; very small delays, e.g., 1 ms, would obviously cause little performance degradation. On the other hand, very large delays, e.g., 2 s, make bilateral teleoperation problematic in any architecture.

Stability of each architecture is evaluated using the passivity approach of Section V. Since passivity theory (Theorem 2) only provides a sufficient condition for stability, with no measure of stability margin, it is not clear from Theorem 2 alone that performance in a given application will be satisfactory. That is, the system may satisfy the theorem, yet have an arbitrarily small stability margin. Also, the system may be quite stable, even if the passivity conditions are violated. Since the examples here are scalar, the Nyquist criterion can be used to exactly determine system stability and stability margins, e.g., gain and phase margin. To apply this criterion, it is helpful to redraw the block diagram of Fig. 2 in the form of Fig. 9. If a particular loop in Fig. 9 contains only stable subsystems, then this loop is stable if the Nyquist plot of the loop frequency response does not encircle the critical point \(-1 + j0\) in the complex plane. There are three levels of loops in Fig. 9. The lowest level comprises the individual master and slave control systems \(c_m\) and \(c_s\). We assume these are stable loops. The loop \(LG1\), given by

\[
LG1 = \frac{c'_1(c'_2 - z_kc'_3)}{(z_m + c'_m + z_h)(z_s + c'_s)}
\] (38)

is therefore made up of stable subsystems, and this loop is stable if \(LG1\) does not encircle the critical point. If this holds, then the primary loop \(LG2\), defined by

\[
LG2 = \frac{z_s(z_m + c'_m + z_h(1 - c'_1c'_2) + c'_1c'_3)}{(z_s + c'_s)(z_m + c'_m + z_h) - c'_1(z_s + c'_3) - c'_1}
\] (39)

contains only stable subsystems. The entire teleoperation system is therefore stable if \(LG2\) also does not encircle the critical point. If this holds, then the primary loop \(LG2\), defined by

\[
\lim_{z_s \to 0} \frac{z_t}{z_s} = \frac{[m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]}{[m_s + b_s + k_s /s] + [m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]} \quad (40)
\]

Note for large \(z_s\), relative to the other terms in (40) (e.g., slave contact with a stiff environment), the transmitted impedance becomes

\[
\lim_{z_s \to \infty} \frac{z_t}{z_s} = \frac{[m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]}{[m_s + b_s + k_s /s] + [m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]} \quad (41)
\]

which shows that the operator only feels the dynamics of the master and its control system. On the other hand as \(z_s\) becomes small (e.g., slave in free space motion) we have

\[
\lim_{z_s \to 0} \frac{z_t}{z_s} = \frac{[m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]}{[m_s + b_s + k_s /s] + [m_m + (m_m b_s + m_s b_h) + (m_m b_s + k_m m_s)/s]} \quad (42)
\]

Due to the free \(s\) term in the numerator of this impedance, it has a feel which approximates an inertia, at least for low frequency motion. As mentioned in the Introduction, good position control on the master (large \(k_m\), \(b_m\)) increases the size of this effective inertia, leading to a sluggish feel in free space teleoperation. For both extremes of \(z_s\), the operator feels dynamics associated with the teleoperator system, not the dynamics of the task. Thus, the position–position architecture does not provide transparency, at least at the extremes of task impedances \(z_s\).

Another view of transparency can be obtained by fixing \(z_r\) at some nominal value, and examining the frequency domain behavior of the achieved \(z_t\) from (36). For example, picking the following values for master and slave mechanical dynamics (corresponding to a typical slave manipulator and a relatively light, small master)

\[
m_m = 0.1 \text{ lb.s}^2/\text{in} \quad m_s = 0.50 \text{ lb.s}^2/\text{in} \quad (43)
\]

and the control parameters (good position control on the slave, moderate position control on the master)

\[
b_m = 2.0 \text{ lb.s/in} \quad k_m = 10 \text{ lb/in} \quad b_s = 10 \text{ lb.s/in} \quad k_s = 50 \text{ lb/in} \quad (44)
\]

A. Position–Position Architecture

Using the forms of subsystem blocks from Fig. 3 in the general expression (36), we obtain the impedance transmitted to the operator \(z_t\):

\[
\left[\begin{array}{c}
[m_m m_s s + (m_m b_s + m_s b_h) + (m_m k_s + k_m m_s)/s] \\
+[m_m s + b_m + k_m /s] z_t/
\end{array}\right] \\
\left[\begin{array}{c}
[m_s s + b_s + k_s /s] + z_t /
\end{array}\right]. \quad (40)
\]

Fig. 9. Reformulation of the general teleoperator architecture to determine closed-loop stability via the Nyquist criterion.
together with the environment impedance of
\[
z_r = k_r/s; \quad k_r = 100 \, \text{lb/in}
\] (45)
yields the frequency response magnitude and phase measures of transparency for \(z_t\) shown in Fig. 10. The passive-delay communication link characterized by (27) and (36) is included in this simulation, and hence is similar to the architecture suggested in [6]. Ideally, the ratio \(z_t/z_r\) should have a magnitude of unity (0 dB) and a phase of 0 rad.

It is difficult to give a precise description of what the operator feels from this impedance, but it is clear that the transmitted stiffness can be very much different than the stiffness of \(z_r\). The loop gain plots in Fig. 10 show that the teleoperator system is stable, at least in this specific case where
\[
z_h = 0.1 \, \text{s} + 1.0 + 1.0/s \, \text{lb/in}
\] (46)
which corresponds to an operator with the master firmly in hand, but with very little arm tension. In particular, the Nyquist plot of the overall loop gain \(LG2\) has a phase margin of about 90 degrees (plot scale is chosen to see phase margin more clearly). The plots of the two components of the \(P(s)\) matrix from (22) show that passivity conditions for stability according to Theorem 2 are not satisfied (real parts are not always positive). Since in the expression (22) for \(P4, C_4\) is "negative" (see Fig. 3), a nonpassive \(P\) is a characteristic of the position–position architecture. Larger delays eventually destroy stability, as would be seen in the Nyquist plot of LG1 in Fig. 10 as an ever larger spiral as the delay is increased, eventually encircling the critical point.

B. Position–Force Architecture

Substituting the appropriate values of system blocks from Fig. 3 into the expression (36), we obtain the following impedance transmitted to the operator using the position–force architecture in the no-delay case.

\[
z_t = \left[ m_s s + b_s + k_s/s \right] + \left[ m_m s + k_f(b_s + k_s/s) \right] \frac{z_r}{z_r + \left[ m_s s + b_s + k_s/s \right] + z_r}
\] (47)

For large \(z_r\) we have
\[
\lim_{z_r \to \infty} z_t = \left[ m_m s + k_f(b_s + k_s/s) \right]
\] (48)

hence the operator feels the inertia of the master, plus a scaled version of the damping and stiffness of the slave. When \(z_r\) becomes small
\[
\lim_{z_r \to 0} z_t = \left[ m_m s \right]
\] (49)

and the operator only feels the master inertia. Using the same nominal system parameters as in (42)–(44), except that \(b_m = 0.1 \, \text{lb/s}, k_m = 0, \) and \(k_f = 1\) (corresponding to a typical
control on the master in the position–force case), the frequency response of $z_t$ is shown in Fig. 11. This plot contains the effects of a passive-delay communication link, hence would be similar to the architecture [7] if interaction forces were communicated rather than their “coordinating force.”

We can see that the low frequency error between task impedance and transmitted impedance can be quite large. This reflects a large error in the apparent stiffness presented to the operator, compared to the task stiffness. Although the transmitted impedance is similar to the position–position architecture this position–force example is more prone to stability problems. The phase margin of the primary loop $LG2$ is only about 45 degrees. Since the loop gain $LG2$ is proportional to the environmental stiffness $k_e$ (see (39)), larger stiffnesses would make the system very oscillatory in contact with the task. As mentioned in the Introduction, this is a common difficulty with the force feedback approach [2], [16]. Stability can be improved by reducing the force feedback gain $k_f$, but at the cost of reduced sensitivity. (Although in some cases, this is desirable, e.g., when large loads are to be manipulated [2], [22]). Still, it is clear that the force feedback architecture is not optimal in the sense of transparency. Finally, note that the $P4$ component of $P(s)$ is decidedly not passive. A closer examination of the expression for $P4$ from (22) reveals why this is the case. Since $c_4 = 0$ (no position feedback from the slave), and $c_2z_e$ looks like $1/s$, we see that $P4$ is of the form $s^2$ at high frequencies, and cannot be passive. Consequently, stability of the system is not immune to increasing communication delays, as would be seen as a general increase in the CW rotation of the Nyquist plot of $LG2$ in Fig. 11, resulting in eventual instability.

C. “Passivated” Position–Force Architecture

The architecture of [7] has two essential characteristics: a passive communication link, and a feedback of a “coordinating force” $F_e$ rather than the environmental force $F_e$. In the formulation of this paper, the corresponding operator $L$ is passive (strictly passive with the loss-factors suggested here), and the operator $P$ is always passive. This can be seen by placing the architecture in the form of Fig. 2, where it turns out that the (undelayed) control laws have the form

$$c_1 = b_s + k_s/s$$  \(50\)
$$c_2 = \alpha_f + 1 \text{ constant}$$  \(51\)
$$c_3 = 0$$  \(52\)
$$c_4 = z_s$$  \(53\)
$$c_s = b_s + k_s/s$$  \(54\)
$$c_m = 0.$$  \(55\)

Since $c_4$ contains an $s$ term due to the inertial component of $z_s$, $P4$ from (22) looks like a (positive) constant at high frequencies. This approach results in guaranteed stability for the teleoperator system, but poor transparency as shown in Fig. 12. This simulation used the same values for system parameters as in the earlier cases, and $\alpha_f = 100$. This architecture
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has similar transparency performance as the position–position case, but much better passivity and stability properties. In fact, as noted in [7] and proved here in Theorem 2, this teleoperator architecture is stable for any time delay. This property can also be seen in a conventional sense by observing that added phase shifts due to delays in LG1 and LG2 will have no effect on critical point encirclements. Even though stability is retained, poor transparency at large delays will make bilateral teleoperation impractical. Even for moderate delays, however, this architecture can be expected to provide relatively poor transparency performance.

D. Transparency-Optimized Architecture

The control laws (9) and (10), which provide perfect transparency, are simplified as suggested in (12) to obviate acceleration measurements. (See [14] for a two-DOF implementation which makes use of acceleration in a similar architecture). Using the values of \( z_m, z_c, c_m \) and \( c_c \) as in the position–position architecture, the performance of the "transparency optimized" architecture is shown in Fig. 13. Again, the passive-delay communication link is included. This architecture provides extremely accurate impedance transmission at low frequencies, indicating that this system would faithfully reproduce task stiffness to the operator. It should be noted that the "passivation" introduced to counter the effects of communication delay does not degrade the low frequency transparency in this architecture. In contrast, [6] suggests that wave reflections in the communication link may significantly degrade performance in an architecture which does not explicitly consider transparency. Thus, the type of information transmitted (the overall architecture) may be more important than the way information is transmitted (the specific form of a teleoperator subsystem).

As in the other architectures, transparency begins to degrade in Fig. 13 at about 10 rad/s. The phase margin of the LG2 loop is about 45 degrees (similar to the position–force architecture). Note that perfect low frequency transparency has been obtained with physically reasonable control laws using this general architecture of Fig. 2, unlike [13] which requires infinite gains to achieve the same performance. Even though the system is stable, the plots of the \( P1 \) and \( P4 \) components of the \( P(s) \) matrix reveal that the system is not passive. The reason for this can be seen in the expression below (22) for \( P4 \). Optimal transparency requires that \( c4 \) is "negative" according to (12), preventing this architecture from ever satisfying the conditions of Theorem 2, unless the task impedance \( z_c \) contains significant inertial behavior. Thus, passivity (and a certain degree of stability, e.g., insensitivity to communication delay) has been traded for an increase in transparency performance.

VII. CONCLUSION

Since a bilateral teleoperation system interacts dynamically with the environment (task) and the human operator, static
performance considerations do not provide sufficient tools for designing high performance teleoperation systems. Analysis tools were provided in this paper for examining transparency and stability of a general teleoperation architecture. These tools provide guidance in selecting control laws to optimize transparency, and to mitigate the effects of communication delays between master and slave.

Several bilateral teleoperation architectures were quantitatively compared in terms of transparency and stability. The common position–position and position–force architectures provide poor transparency, even at low frequencies, and poor stability properties (neither one can provide a passive teleoperator block \( P \) for use in Theorem 2). A “passivated” version of the position–force scheme [7] provides significant improvement in passivity, hence stability, but does not improve transparency. An example of a “transparency optimized” design was given which required the use of all four possible information channels. This architecture provides accurate low frequency transparency, but cannot generally provide a passive operator \( P \). These examples show that passivity (stability) and transparency are conflicting objectives in teleoperator system design. Passivity-based architectures [7], [6] and transparency-based approaches (as developed here and in [14]) therefore lie at opposite ends of this “optimal” stability/performance spectrum. As shown here, conventional architectures fall significantly short of “optimum” in either sense. If the level of transparency needed for safe, nonfatiguing execution of remote tasks is not extreme, relatively large stability margins can be obtained using the passivity-optimized approach. This would allow operation in the presence of relatively large communication delays. However, if higher transparency levels are desired, a transparency-optimized approach would be needed, and smaller allowed communication delays can be expected. Unfortunately, the question of what levels of transparency are necessary for efficient task execution has seen little quantitative study, hence the stability/transparency trade-off remains an important area for further research.

The simplified scalar (one degree of freedom) examples presented in this paper provide guidance in the design of realistic (multivariable) teleoperation systems. However, except in the case of kinematically similar master and slave with direct joint-to-joint intercommunication, where a large degree of decoupling exists, the detailed specification of desired levels of transparency and stability remains an open problem. Recent developments using “robust” multivariable notions, such as small gain theory [23], passivity [24], and combinations [20], [10]) provide some tools, but the resulting designs can often be overly conservative (preventing high performance) or not very robust (can allow arbitrarily small stability margins). However, shaping recent developments in multivariable control theory to suit the teleoperation problem has a potentially large payoff. Results in this area may significantly extend the capabilities of

Fig. 13. Transparency ratio frequency response of the “transparency optimized” teleoperator architecture (solid lines) versus the desired impedance ratio of 1 (dotted lines).
remote manipulation systems to the point where they can be effective replacements for humans in many manipulation tasks.

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