# Stable Adaptive Teleoperation

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*(Invited Paper)*

*Abstract*—**Telerobotics, the body of science and technology which bridges human control and purely autonomous machines, is expected to be a merging point of modern developments in robotics, control theory, cognitive science, machine design, and computer science. Besides traditional applications in space, subsea, and handling of hazardous material, many new potential uses of advanced telerobotic systems have recently been suggested or explored, such as safety applications or microsurgery.**

**This paper studies how the existence of transmission time-delays affects the application of advanced robot control schemes to effective force-reflecting telerobotic systems, which would best exploit the presence of the human operator while making full use of available robot control technology and computing power. A physically motivated, passivity-based formalism is used to provide energy conservation and stability guarantees in the presence of transmission delays. The notion of wave variable is utilized to characterize time-delay systems and leads to a new configuration for force-reflecting teleoperation. The effectiveness of the approach is demonstrated experimentally. Within the same framework, an adaptive tracking controller is incorporated for the control of the remote robotic system and can be used to simplify, transform, or enhance the remote dynamics perceived by the operator.**

## I. Introduction

TELEROBOTICS (under various names) has a long and rich history (see, e.g., [11, and references therein]). It is likely to provide a common field of research and applications to many recent and parallel developments in a wide range of areas, such as robotics, control theory, cognitive science, machine design, and computer science.

This paper represents a preliminary study on how the existence of time-delays affects the application of advanced control schemes to effective force-reflecting telerobotic systems. Using tools from passivity theory, it attempts to understand how recent results in adaptive robot control may be applied effectively to simplify, transform, or enhance the remote dynamics perceived by the operator.

Force feedback can considerably improve an operator's ability to perform complex tasks that interact with a remote environment, such as assembly or surface following and inspection. However, in the presence of transmission delays (whether caused by low-bandwidth transmission lines, slow acoustical connections, or long satellite transmissions), force feedback has a strong destabilizing effect. It is therefore important to carefully understand the limitations imposed on force-reflection by stability needs. In current force-reflecting teleoperation applications, this problem is often dealt with by adding large amounts of damping at various locations throughout the system. Besides providing no formal stability guarantee, such design can considerably limit performance and, furthermore, is typically very sensitive to the parameters describing the system.

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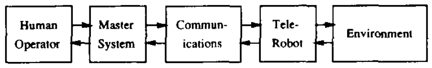



Fig. 1. Structure of the teleoperation system.

Many reasons can also be cited for using advanced control techniques to simplify the perceived remote dynamics. The operator of a complex teleoperation system should not be expected to deal with the inherent robotic or control issues—he or she has real work to do. For instance, a marine biologist remotely studying or sampling some unknown organisms in a cluttered underwater environment should not be expected to fight rapid variations in currents or drag, or to deal with the nonlinear dynamic couplings in some sophisticated underwater manipulator arm. For him or her, the remote robot should act and feel like a video game. In addition, the transmission time delays typical in many telerobotic applications make it all the more important to provide consistently high performance locally at the remote manipulator, limiting the need for corrective actions by the operator. The remote dynamics may also be transformed or enhanced so as to provide the operator with clearer cues or help in decision-making; e.g., through proper frequency shaping of the sensed signals.

In this paper we use a passivity-based formalism to construct a teleoperation system which imitates physical systems and consequently obeys an energy conservation law. Imagine, for example, a mass at the end of a long string. While such a system includes a delay and force reflection, it is always stable because it has no energy sources. Furthermore, careful motion of the tip of the string can produce a desired motion of the mass. Applications of such ideas to teleoperation have already been suggested in the literature, most remarkably in the important work of [1]. Yet a detailed analysis and systematic design approach are still outstanding, since the time delays make the use of traditional tools (such as Laplace transforms) difficult. Using the notions of wave variable and wave transmission, this paper aims at providing a deeper understanding of the dynamics of time-delayed transmissions and of their interactions with nonlinear dynamic systems. Furthermore, it leads to a new design approach for teleoperation systems, which in essence inserts the communications between two impedance controllers and automatically converts the applied forces at both locations into setpoints for the opposite site. The development is illustrated experimentally.

Using the passivity formalism also allows the teleoperation system to be separated into multiple elements (Fig. 1). We can therefore consider the communications independently from the particular operating configuration and concentrate on the difficulties created by the time delay. It is furthermore possible to simply connect to the adaptive control scheme of [12], [7], and [8] for the remote manipulator, which can also be described in a passivity-based formalism.

After briefly reviewing the basic concepts of passivity in

Section II, we analyze the communications in Section III using wave variables in place of the standard power variables. Specifically, we study the effects of time delays on energy conservation arguments, review how a physical system may be imitated, and consider possible problems with wave reflections. With these insights, we discuss a new structure for the communications in Section IV, and, in Section V, other applications of wave variables, in particular, to filtering. Section VI makes some suggestions for more advanced teleoperation setups, which use model-based predictions of the remote system behavior. Section VII incorporates adaptive control of the remote manipulator, and brief concluding remarks are offered in Section VIII.

## II. Basic Passivity Concepts

The passivity formalism [9], [4] represents a mathematical description of the intuitive physical concepts of power and energy. It provides a simple and robust tool to analyze the stability of a nonlinear system and allows for connections to other systems while maintaining global stability properties. The formalism is briefly summarized here. The reader is referred to [13] for a detailed presentation.

Define the "power" $P$ entering a system as the scalar product between the input vector $\boldsymbol{x}$ and the output vector $\boldsymbol{y}$ of the system. Note that this power does not necessarily correspond to any actual physical power if the input/output variables are not chosen to be co-located velocity and force signals. In addition, define a lower-bounded "energy storage" function $E$ and a non-negative "power dissipation" function $P_{\text{diss}}$, which again need not represent true physical quantities.

With these definitions a system is said to be passive, if it obeys:

$$P = \boldsymbol{x}^T \boldsymbol{y} = \frac{dE}{dt} + P_{\text{diss}} \tag{1}$$

i.e., if the power is either stored or dissipated. This implies that the total energy supplied by the system up to time $t$ (corresponding to a negative energy transfer into the system) is limited to the initial stored energy; i.e., the energy transfer is lower bounded by the negative initial energy:

$$\int_0^t P\, d\tau = \int_0^t \boldsymbol{x}^T \boldsymbol{y}\, d\tau = E(t) - E(0) + \int_0^t P_{\text{diss}}\, d\tau \geq -E(0) = \text{constant}.$$

If the power dissipation is zero for all time, the system is also termed lossless. In contrast, if the power dissipation is positive as long as the stored energy has not reached its lower bound, the system is strictly passive.

Using the stored energy as a Lyapunov-like function, one can quickly analyze stability and show that, without external input, a passive system is stable. Asymptotic stability is obtained for a strictly passive system, assuming that the stored energy depends positively on all states of the system.

A further and important practical feature of the passivity formulation is its closure properties. This implies that the combination of two passive systems connected in either a feedback or parallel configuration is again passive. In particular, the stored energy and power dissipation of the combined system is obtained by adding the individual functions of both systems. In the case of force-reflecting teleoperation, using a passive control strategy then allows the manipulation of an arbitrary passive environment without loss of the global stability properties. This is most valuable, as operating conditions may vary significantly and in an unknown fashion.

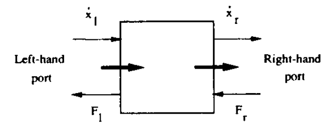



Fig. 2. Distinguishing left- and right-hand ports in a passive 2-port element.

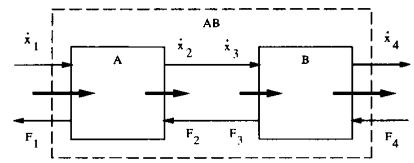



Fig. 3. Cascading of 2-port elements retains passivity.

While the passivity formalism is clearly motivated by physical intuition, it can apply to systems with arbitrary input and output variables of the same dimension. Therefore the "power" and "energy" functions need not correspond to any real physical quantities. With this understanding in mind, we will continue to refer to them as power and energy for simplicity.

In summary, the use of a passive control strategy constitutes a sufficient condition for the stability of the system coupled to a passive environment with a bounded operator input energy. In addition, it represents a necessary condition for the stability with *any* remote environment. The use of passivity to analyze contact stability in the case of a linear manipulator system is extensively discussed in [3].

### A. Power Flow for 2-Port Elements

The passivity formalism applies to multi-degree-of-freedom and multiport systems. In all cases the input variables and the output variables can be lumped into a single vector of inputs and a single vector of outputs. However, to provide a simpler notation for the analysis in the remaining sections, we now define a convention particular to 2-port elements.

In the general description above, all power was declared positive if it were entering the system and increasing the stored energy. In the 2-port case, however, it makes sense to distinguish a left-hand port $l$, which has positive power entering the system, and a right-hand port $r$, which has positive power exiting the system, as shown in Fig. 2. Therefore the total power flow, which governs the stored energy change according to (1), is now given by

$$P = \dot{\boldsymbol{x}}_l^T \boldsymbol{F}_l - \dot{\boldsymbol{x}}_r^T \boldsymbol{F}_r.$$

This sign definition allows for the simple cascading of elements to insure the closure properties of passivity. Fig. 3 shows two passive 2-port elements, which are cascaded into an overall passive 2-port element. This is quickly verified, noticing that

$$\begin{aligned} P &= \dot{\boldsymbol{x}}_1^T \boldsymbol{F}_1 - \dot{\boldsymbol{x}}_4^T \boldsymbol{F}_4 \\ &= \dot{\boldsymbol{x}}_1^T \boldsymbol{F}_1 - \dot{\boldsymbol{x}}_2^T \boldsymbol{F}_2 + \dot{\boldsymbol{x}}_3^T \boldsymbol{F}_3 - \dot{\boldsymbol{x}}_4^T \boldsymbol{F}_4 \\ &= \frac{dE^A}{dt} + P_{\text{diss}}^A + \frac{dE^B}{dt} + P_{\text{diss}}^B = \frac{dE^{AB}}{dt} + P_{\text{diss}}^{AB} \end{aligned}$$

where $E^{AB} = E^A + E^B$ is the lower-bounded energy storage function, and $P_{\text{diss}}^{AB} = P_{\text{diss}}^A + P_{\text{diss}}^B$ is the non-negative power dissipation function of the combined system.

### B. Wave Variables and Wave Scattering

The notion of wave scattering is closely related to the passivity formulation. It separates the total power flow into two parts, representing the power input and power output of the system. These two parts are then associated with input and output waves. This is again motivated by the physical concept of waves, but can also be applied to any nonlinear system.

Formally treated in scattering theory, waves can be interpreted within the passivity formulation in the following manner. Assuming a 2-port element with a left-hand port $l$ and a right-hand port $r$ as defined above, the total power flow can be rewritten as

$$P = \dot{x}_l^T F_l - \dot{x}_r^T F_r = \frac{1}{2} u_l^T u_l - \frac{1}{2} v_l^T v_l + \frac{1}{2} u_r^T u_r - \frac{1}{2} v_r^T v_r.$$

Here the vectors $u_l$ and $u_r$ clearly increase the power flow into the system and are interpreted as *input waves* of the respective port. Similarly, the vectors $v_l$ and $v_r$ decrease the power flow and are interpreted as *output waves*. The above equation implicitly defines a transformation between the power variables $(\dot{x}, F)$ and wave variables $(u, v)$ at both ports, described by

$$u_l = \frac{1}{\sqrt{2b}} (F_l + b\dot{x}_l), \qquad u_r = \frac{1}{\sqrt{2b}} (F_r - b\dot{x}_r)$$
$$v_l = \frac{1}{\sqrt{2b}} (F_l - b\dot{x}_l), \qquad v_r = \frac{1}{\sqrt{2b}} (F_r + b\dot{x}_r). \quad (2)$$

Though the strictly positive parameter $b$ can be chosen arbitrarily, it defines a *characteristic impedance* associated with the wave variables and directly effects the system behavior. Proper choice of this impedance is thus critical for achieving an acceptable response, as Section III-D will detail.

The wave transformation is one-to-one and can be inverted to provide the power variables as a function of the wave variables:

$$F_l = \sqrt{\frac{b}{2}} (u_l + v_l), \qquad F_r = \sqrt{\frac{b}{2}} (u_r + v_r)$$
$$\dot{x}_l = \frac{1}{\sqrt{2b}} (u_l - v_l), \qquad \dot{x}_r = -\frac{1}{\sqrt{2b}} (u_l - v_l). \quad (3)$$

Moreover, each port is also uniquely determined if one wave variable and one power variable are specified. We can therefore connect a system, defined in wave variables and determining the output waves $v$, to systems which provide *either* velocity or force commands. For example, if the left-hand port force $F_l$ and the right-hand port force $F_r$ are given, the wave transformations are

$$u_l = \sqrt{\frac{2}{b}} F_l - v_l, \qquad u_r = \sqrt{\frac{2}{b}} F_r - v_r$$
$$\dot{x}_l = \frac{1}{b} (F_l - \sqrt{2b}\, v_l), \quad \dot{x}_r = -\frac{1}{b} (F_r - \sqrt{2b}\, v_r). \quad (4)$$

Equivalently, if the left-hand port velocity $\dot{x}_l$ and the right-hand port velocity $\dot{x}_r$ are given, the wave transformations can be written as

$$u_l = \sqrt{2b}\, \dot{x}_l + v_l, \qquad u_r = -\sqrt{2b}\, \dot{x}_r + v_r$$
$$F_l = b\dot{x}_l + \sqrt{2b}\, v_l, \qquad F_r = -b\dot{x}_r + \sqrt{2b}\, v_r. \quad (5)$$

In particular, it is also possible to specify a velocity command at one port while imposing a force command at the other port. Fig. 4 shows the transformations graphically for the case that the left-hand port velocity $\dot{x}_l$ and the right-hand port force $F_r$ are given.

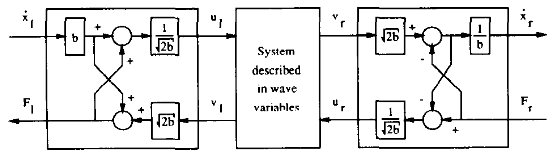



Fig. 4. Wave transformation using $\dot{x}_l$ and $F_r$ as inputs.

Note that the characteristic wave impedance $b$ can be generalized to a positive definite matrix as well as a time-varying and even state-dependent operator. Identical effects, however, can also be achieved by adding passive (possibly nonlinear) elements to both ports of the system and defining independent $b_i$'s for each dimension of the system. Without loss of generality, we now restrict $b$ to be a strictly positive scalar constant.

Relating wave scattering to passivity, a system is passive if the energy provided by the output waves is limited to the energy received via the input waves:

$$\int_0^t \frac{1}{2} v^T v \, d\tau \le \int_0^t \frac{1}{2} u^T u \, d\tau.$$

This is satisfied for all cases where the output wave amplitude is bounded by the amplitude of the possibly delayed input wave. We can therefore include arbitrary time delays into systems described by wave variables in a passive and hence stable fashion. This is one of the fundamental features which motivate this work.

As $t \to \infty$, the ratio of the output to input energy is determined by the $H_\infty$ norm of the system. This provides the relation of both wave scattering and passivity to the *small gain theorem*, which states that a closed-loop system is stable if the $H_\infty$ norm of the open-loop system is limited to unity. Thus a passive system, when expressed in wave variables and provided with a feedback signal, satisfies the small gain theorem and is stable. This confirms the stability results for passive systems derived earlier using a Lyapunov-like approach.

## III. Communication with Time Delays

The communications element in a teleoperation setup connects the local and remote systems and closes the overall control loop by transmitting data to and from both sites. It typically also introduces time delays, which may be caused by physical transmission times or communication bandwidth limitations. The type of the transmitted data, however, can be chosen freely and affects the behavior and stability of the overall system quite drastically. In particular, a transmission can be set up to enable stable force-reflecting teleoperation with arbitrary large time delays, as the following shows.

### A. Instabilities Caused by Time Delays

The introduction of time delays can quickly give rise to instabilities in most any feedback system, a fact leading, for example, to the notion of phase margin in linear control theory. In force-reflecting teleoperation, such delays occur in the communications between the local and remote sites. As is well known, even small delays can cause a system instability. This behavior can be attributed to the communications alone and is not dependent on the particular controller or hardware configuration, although appropriate controllers and hardware may reduce the danger of instability.

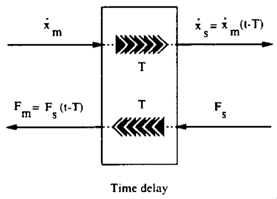



Fig. 5. Standard communications for force reflection.

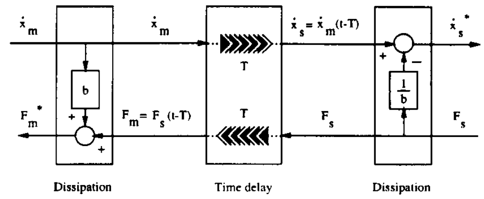



Fig. 6. Standard communications stabilized with sufficient dissipation.

Using a passivity-based analysis, as detailed next, it is possible to separate the communications from the remaining subsystems and to detail how instabilities arise as a consequence of the time delay. Furthermore, given passive local and remote subsystems (containing the controllers and possibly environments), using a passive communication is sufficient to ensure the stability of the complete system. It is also necessary if the subsystems remain unspecified (even if passive), as is the case when manipulating arbitrary environments.

The standard communications between local and remote sites are described by a 2-port element, with one port connecting to the local controller/manipulator and the other to the remote system. Typically, the structure of this element is such that the local velocity is transmitted to the remote site, becoming a velocity command. Simultaneously, the remote force is transmitted back to the local site to provide the desired force command. Thus a standard communications procedure is shown in Fig. 5, given by

$$\dot{x}_s(t) = \dot{x}_m(t - T)$$

and

$$F_m(t) = F_s(t - T)$$

where $T$ is the time delay involved. The subscript $m$ (for master) denotes variables at the local site, while the subscript $s$ (for slave) refers to variables at the remote location.

Examining the power flow into the system provides the following analysis. Note that separate degrees of freedom are independent in the communications and thus, for notational simplicity, only a single degree of freedom is treated here. Also, the gain $b$ relates the different units of force and velocity and can be interpreted as a characteristic impedance. The power flow is determined by

$$\begin{aligned} P &= \dot{x}_m(t)F_m(t) - \dot{x}_s(t)F_s(t) \\ &= \frac{1}{2b}F_m^2(t) + \frac{b}{2}\dot{x}_m^2(t) - \frac{1}{2b}(F_m - b\dot{x}_m)^2(t) \\ &\quad + \frac{1}{2b}F_s^2(t) + \frac{b}{2}\dot{x}_s^2(t) - \frac{1}{2b}(F_s + b\dot{x}_s)^2(t) \\ &= \frac{1}{b}F_m^2(t) - \frac{1}{2b}(F_m - b\dot{x}_m)^2(t) \\ &\quad + b\dot{x}_s^2(t) - \frac{1}{2b}(F_s + b\dot{x}_s)^2(t) \\ &\quad + \frac{d}{dt}\int_{t-T}^{t} \frac{b}{2}\dot{x}_m^2(\tau) + \frac{1}{2b}F_s^2(\tau)\, d\tau. \end{aligned} \tag{6}$$

Therefore defining the stored energy $E$ and power dissipation $P_{\text{diss}}$ as

$$E = \int_{t-T}^{t} \frac{b}{2}\dot{x}_m^2(\tau) + \frac{1}{2b}F_s^2(\tau)\, d\tau$$

and

$$\begin{aligned} P_{\text{diss}} &= \frac{1}{b}F_m^2(t) - \frac{1}{2b}(F_m - b\dot{x}_m)^2(t) \\ &\quad + b\dot{x}_s^2(t) - \frac{1}{2b}(F_s + b\dot{x}_s)^2(t) \end{aligned} \tag{7}$$

determines the rate of change of stored energy as

$$\frac{d}{dt}E = P - P_{\text{diss}}.$$

For the communications to be passive, the power dissipation $P_{\text{diss}}$ must always be positive. However, specific choices of the input variables $\dot{x}_m$ and $F_s$ will cause a negative dissipation; i.e., will produce energy which can drive the overall system unstable. Hence the standard form of communications is not passive. Anderson and Spong [1] derived similar results using a scattering operator defined in the Laplace domain.

This result does not immediately imply that the system must be unstable. It simply states that there always exists a controller/manipulator setup (which may even be passive), such that the overall system is unstable. Actually, there are many such setups, including some of the simplest nature, as illustrated in the Appendix. Therefore it is most undesirable to have nonpassive communications, as the overall system stability then depends strongly on the particular controllers and the particular parameter values, including the value of the delay. In order to provide a robust teleoperation system and guarantee stability for any passive controller and environment, the communications should itself be chosen to provide a passive subsystem.

### B. Stabilizing the Standard Communications

In the previous section we saw that the standard communication setup may indefinitely inject energy into the system, leading to instabilities. In most current teleoperation applications this-problem is dealt with by making the system "sufficiently well-damped"; i.e., by limiting the speed of motion and consequently dissipating the produced energy at a variety of locations throughout the system. While such an approach may lead to a practically acceptable system, it lacks any stability or performance guarantees and is typically dependent on all elements of the system, including the actual value of the time delay.

As we now show, such problems can be circumvented by placing dissipating elements directly next to the communications (Fig. 6), guaranteeing passivity properties regardless of the delay and of the remainder of the system. However, the dynamics are also changed and some unwanted effects are introduced. Thus this approach may not as such be suitable for direct application and is mainly included here because it bridges the standard nonpassive communications to the passive communications that are introduced in the following sections (see in particular the later part of Section III-D).

The power flow of the standard communications (equation (6))

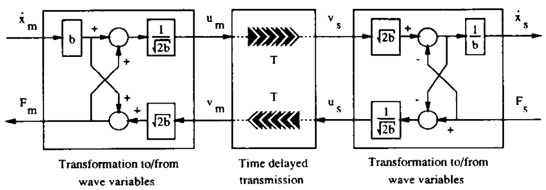



Fig. 7. Time-delayed transmission of wave variables.

can be expanded to include the additional dissipation, resulting in the modified power flow:

$$
\begin{aligned}
P &= \dot{x}_m(t)F_m^*(t) - \dot{x}_s^*(t)F_s(t) \\
&= \frac{1}{b}F_m^2(t) - \frac{1}{2b}(F_m - b\dot{x}_m)^2(t) + b\dot{x}_s^2(t) \\
&\quad - \frac{1}{2b}(F_s + b\dot{x}_s)^2(t) \\
&\quad + \frac{d}{dt}\int_{t-T}^{t} \frac{b}{2}\dot{x}_m^2(\tau) + \frac{1}{2b}F_s^2(\tau)\,d\tau \\
&\quad + b\dot{x}_m^2(t) + \frac{1}{b}F_s^2(t) \\
&= \frac{1}{2b}F_m^{*2}(t) + \frac{b}{2}\dot{x}_s^{*2}(t) \\
&\quad + \frac{d}{dt}\int_{t-T}^{t} \frac{b}{2}\dot{x}_m^2(\tau) + \frac{1}{2b}F_s^2(\tau)\,d\tau.
\end{aligned}
$$

Thus the total dissipation is positive, meaning that the additional dissipations elements are removing all produced energy, and the modified communications are passive, regardless of the actual time delay $T$.

The above implies that, in such a setup, dissipation occurs as long as either output $\dot{x}_s^*$ or $F_m^*$ is nonzero. Therefore a continuous power input is required to sustain a constant motion. This is actually quite acceptable and maybe even desirable, since it simply states that in the absence of operator action the system will come to a rest by itself. However, a continuous power input is also required to sustain a constant force reflection. This is not acceptable, because it implies that at rest (i.e., when there is no power flow), the operator cannot feel or apply a constant force to the remote environment. Furthermore, the process of dissipation modifies the velocity commands whenever forces are reflected, so that the remote manipulator position will drift away from the master manipulator. Thus while the remote manipulator will track the master velocity, it will not converge to the master position.

## C. Imitating Natural Wave Phenomena

Time delays are by no means particular to man-made systems, but occur naturally and stably in physical phenomena such as wave propagation. For example, an electrical transmission line of given length represents a passive system, yet includes a finite delay-time and exhibits wave behavior. Scattering theory is based on the idea of such wave propagations and allowed [1] to construct a communications procedure mimicking a lossless transmission line, thus retaining passivity in spite of the time delay.

Using the wave-scattering definitions of Section II-B, we immediately see that a passive communication can be achieved simply by *directly transmitting the wave variables* $u$ *and* $v$ *instead of the power variables* $\dot{x}$ *and* $F$. Fig. 7 shows such a system, which is governed by

$$
v_m(t) = u_s(t - T), \qquad v_s(t) = u_m(t - T).
$$

The power flow into such a setup is given by

$$
\begin{aligned}
P &= \frac{1}{2}u_m(t)^2 - \frac{1}{2}v_m(t)^2 + \frac{1}{2}u_s(t)^2 - \frac{1}{2}v_s(t)^2 \\
&= \frac{1}{2}u_m(t)^2 - \frac{1}{2}u_s(t - T)^2 + \frac{1}{2}u_s(t)^2 - \frac{1}{2}u_m(t - T)^2 \\
&= \frac{d}{dt}\left[\int_{t-T}^{t} \frac{1}{2}u_m(\tau)^2 + \frac{1}{2}u_s(\tau)^2\,d\tau\right].
\end{aligned}
$$

Therefore this is a lossless passive communication with a positive energy storage function, which simply integrates the power of the waves for the duration of the transmission. In particular, its passivity property is completely independent of the actual time delay.

Returning to a description in the traditional power variables, the transmission equation can be written as

$$
\begin{aligned}
\frac{1}{\sqrt{2b}}[F_m - b\dot{x}_m](t) &= \frac{1}{\sqrt{2b}}[F_s - b\dot{x}_s](t - T) \\
\frac{1}{\sqrt{2b}}[F_s + b\dot{x}_s](t) &= \frac{1}{\sqrt{2b}}[F_m + b\dot{x}_m](t - T)
\end{aligned}
$$

that is,

$$
\begin{aligned}
F_m(t) &= F_s(t - T) + b(\dot{x}_m(t) - \dot{x}_s(t - T)) \\
\dot{x}_s(t) &= \dot{x}_m(t - T) - \frac{1}{b}(F_s(t) - F_m(t - T)).
\end{aligned}
$$

These expressions represent the same results as obtained by [1] using scattering theory. They also show that by transmitting the wave variables themselves in place of the power variables (force and velocity), *preserving overall stability does not require knowledge of the time-delay* $T$. Furthermore, using the framework of wave variables allows for many additional developments, as will be demonstrated below.

Finally, note that when the actual time delay reduces to zero, transmitting wave variables is identical to transmitting power variables. Thus the above procedure also allows us to naturally *robustify* a system against time delays.

## D. Matching the Wave Impedance

In physical systems, waves are reflected at junctions and terminations; i.e., at points where the impedance of the wave carrier changes. Similarly, using any wave transmission scheme, reflections may occur at both the local and remote sites. To avoid these reflections, which, in the context of teleoperation, corrupt the useful information flow and cause oscillatory behavior, the impedance of the wave transmission must be matched to the remaining system, either by choice of parameters or by including additional *termination* elements.

Systems which include wave propagation and reflections typically also exhibit vibrational characteristics, as, for example, mechanical structures or long flexible tethers. If left undamped, these vibrations may reach magnitudes equivalent to the real signals themselves and prevent any useful operations. Imagine, for instance, controlling the position of a mass at the end of a long string. Clearly the mass can be positioned precisely and without vibration, as is done daily by crane operators. Yet

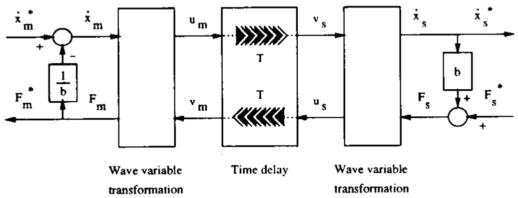



Fig. 8. Wave transmission with matched terminations.

without careful operation, the mass may begin to oscillate and take considerable time to return to a rest position.

Again, as in natural systems, wave reflections can be avoided if the impedance of the attaching subsystem is matched to the characteristic impedance $b$ of the wave transmission. The impedance of any subsystem is given by the gain, which directly relates the force to velocity signal. Assuming a setup as provided in the last section, i.e., commanding the remote velocity and local force, reflections are completely eliminated if the independent power variables can be partitioned as

$$\dot{x}_m = \dot{x}_m^* - \frac{1}{b}F_m, \qquad F_s = F_s^* + b\dot{x}_s \tag{8}$$

where $F_s^*$ and $\dot{x}_m^*$ are independent of $\dot{x}_s$ and $F_m$. The wave transformations are then governed by

$$u_m = \sqrt{\frac{b}{2}}\,\dot{x}_m^*, \qquad u_s = \frac{1}{\sqrt{2b}}F_s^*$$

$$F_m = \frac{b}{2}\dot{x}_m^* + \sqrt{\frac{b}{2}}\,v_m, \qquad \dot{x}_s = -\frac{1}{2b}F_s^* + \frac{1}{\sqrt{2b}}v_s. \tag{9}$$

Comparing to (4) and (5) verifies that reflections are no longer occurring.

Notice from (8) that it is easy to match the wave impedance if the subsystem is accepting a velocity command and producing a force response. In this case the force response must simply include appropriate damping or friction components. In the opposite case, however, the velocity response must depend directly on the force input. This cannot be achieved by any physical system, and therefore an explicit matched termination has to be provided and included into the transmission scheme.

If reflections cannot be avoided within the given configuration by choosing appropriate parameter values, it is also possible to add explicit *matched terminations* to the wave transmission. Such terminations consist of a simple damping element with the same impedance as the transmission and therefore eliminate the undesired reflections. Fig. 8 illustrates the resulting configuration when applied to the transmission scheme introduced in the previous section. Clearly, (8) is satisfied and reflections are canceled. From a power variable perspective, this terminated transmission scheme results in a communication of the form:

$$F_m(t) = \frac{1}{2}F_s^*(t-T) + \frac{b}{2}\dot{x}_m^*(t)$$

$$\dot{x}_s(t) = \frac{1}{2}\dot{x}_m^*(t-T) - \frac{1}{2b}F_s^*(t). \tag{10}$$

Note that in the process of eliminating reflections the terminations also modify the system response. From (10) we see that the slave position command is given by

$$x_s(t) = \frac{1}{2}x_m^*(t-T) - \frac{1}{2b}\int_0^t F_s^*(\tau)\,d\tau$$

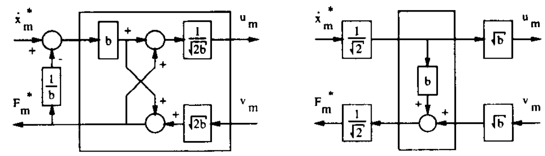


Fig. 9. Equivalence of matched wave and stabilized standard transmission schemes.

which introduces scaling and, more importantly, creates drift between the master position and the slave position if forces are reflected to the operator. A more detailed analysis can be performed to show that a termination at a force-commanded site modifies the velocity commands and causes positional drift. Conversely, a termination at a velocity-commanded site changes the force commands, which implies that master and slave manipulator have a different momentum. Since teleoperation requires kinematic accuracy, the first type of termination should typically be avoided, whereas the second type is perfectly acceptable.

It is interesting to note that the above wave transmission with terminations on both sites corresponds exactly to the stabilized version of the standard transmission, developed in Section III-B, but with the addition of two passive scaling elements. From (9) we see that the transmitted waves are indeed direct measures of the input velocity and force, as is typical for standard communication schemes. Verification of this equivalence can be obtained by examining the underlying equations or interpreting them graphically, as is done in Fig. 9 for the local site.

This equivalence establishes a relation between the wave-transmitting schemes and the standard communication schemes found in typical teleoperational systems. It provides further understanding of the comments on output dissipation and position drift made earlier in Section III-B, and also establishes a systematic and provably stable approach to including additional features within the communications, such as filtering the velocity signal for noise reduction and calculation of the acceleration. Section V will examine such features in more detail.

## IV. A New Configuration for Teleoperation Under Time Delays

Using the passivity approach provides an easy method for guaranteeing stability of a system, yet the actual system performance is not quantified and may or may not be appropriate for the tasks at hand. This is particularly true in the case of time-delayed teleoperation, where the system behavior is quite complex and should degrade smoothly as the delay increases. The communication itself allows numerous configurations and parameter choices which will retain passivity, but which will also drastically alter the overall system performance. This section attempts to understand how these choices affect the system behavior and to develop a useful and well-behaved teleoperation scheme.

As the above section pointed out, wave reflections may occur at both sites and should be avoided if possible. However, wave impedances can only be matched at sites under velocity control, while adding terminations at sites under force control creates position drift. Consequently, it is impossible to implement a force-controlled site without including unwanted reflections.

While impedance matching on just one side of the wave transmission may be enough to prevent large vibrational problems, impedance matching can actually be achieved at both sites *if both sites are placed under velocity control.* Indeed, as mentioned in Section II-B, a wave transmission may accept

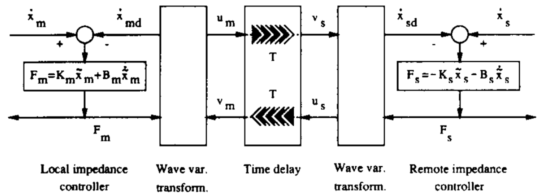



Fig. 10. Wave transmission providing velocity commands to both sites.

either velocity or force input at either site, and also may provide either velocity of force output at either site. Therefore a transmission scheme as in Fig. 10 can be used with both sites receiving force information and providing velocity signals. The communications equations are specified by

$$u_m = \frac{1}{\sqrt{2b}}\left(K_m\tilde{x}_m + B_m\dot{x}_m + (b - B_m)\dot{x}_{md}\right)$$

$$u_s = -\frac{1}{\sqrt{2b}}\left(K_s\tilde{x}_s + B_s\dot{x}_s + (b - B_s)\dot{x}_{sd}\right)$$

$$\dot{x}_{md} = \frac{1}{b + B_m}\left(K_m\tilde{x}_m + B_m\dot{x}_m - \sqrt{2b}\,u_s(t - T)\right)$$

$$\dot{x}_{sd} = \frac{1}{b + B_s}\left(K_s\tilde{x}_s + B_s\dot{x}_s + \sqrt{2b}\,u_m(t - T)\right)$$

while the controller equations are given as

$$F_m = K_m\tilde{x}_m + B_m\dot{\tilde{x}}_m$$

$$F_s = -K_s\tilde{x}_s - B_s\dot{\tilde{x}}_s.$$

To avoid reflections the damping gains, $B_m$ and $B_s$ should be chosen equal to $b$. Additionally, to provide the best performance the proportional gains $K_m$ and $K_s$ should also be similar. Such a scheme then provides a good sense of telepresence if the local and remote manipulators are basically alike. In particular, it is completely transparent when delays are small compared to the typical reaction time of the operator (i.e., delays of up to about a quarter of a second). Furthermore, the performance degrades smoothly as the delay increases.

Although it may seem unusual for a force-reflecting system to operate in such a fashion, the notions of impedance and admittance (see, e.g., [5]) can justify and intuitively explain the structure. Both master and slave manipulators are admittances; i.e., they accept forces from the environment and control system (including the actuators) and convert them into motion. Consequently, any control system connected to a manipulator should behave as an impedance, receiving the motion signals and calculating appropriate forces. To connect two impedance controllers, the transmission must then imitate an admittance. Thus we have a natural chain of impedances and admittances, much like a chain of springs and masses.

Another advantage of this approach is that it makes the overall system symmetric. It corresponds to splitting a single spring-damper system into two pieces and inserting the communications in-between. As the time delay reduces to zero, the two halves simply reconnect, and hence this teleoperation strategy reduces to a simple impedance controller in the limiting case. In contrast, the schemes shown in the previous sections arbitrarily place the impedance controller at one side of the transmission, which results in an unsymmetric system and different behavior at local and remote sites.

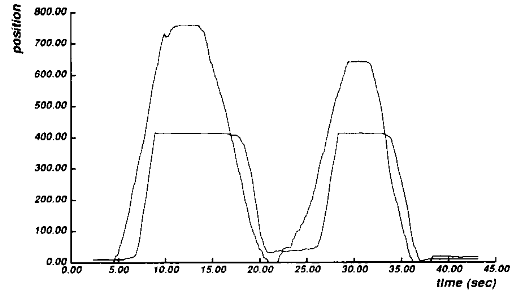



Fig. 11. Positional tracking between the local and remote manipulator.

Fig. 11 shows the result of some preliminary experiments. On a one degree of freedom system a human operator commanded a local trajectory, which lead the remote manipulator to a rigid contact. With a time delay of 1 s, stable position tracking was achieved up to the point of contact, while forces were reflected during the contact. Note that the remote manipulator [10] is inherently back-drivable, so that no force measurements were required to provide the force reflection.

If the two manipulators are significantly different, e.g., in size or weight, the sense of telepresence is distorted by the relative scale. This issue of scaling between local and remote sites, however, is completely independent of the time-delay problems and occurs in any force-reflecting teleoperation system. Scaling gains can be included and may reduce the distortion, yet separate dynamic effects, including inertial, friction, and contact-forces, involve different scaling. Since impedance control does not incorporate any knowledge of these effects and thus does not distinguish between them, simple scaling gains cannot completely eliminate all dynamic distortion. However, the configuration of commanding desired motions at both sites also allows the use of more advanced adaptive control strategies, as we suggest in Section VII, which can address such problems.

Since the local site is now under velocity command, it also provides a position-dependent feedback to the operator. This spring-like behavior can better simulate the feeling of an immediate contact, thus providing more information to the operator than constant force reflections. Predictive feedback can further extend such ideas by actually predicting the behavior of the remote manipulator, as detailed in Section VI.

Finally, knowing that both sites may be placed under velocity or force command, it may be useful to allow each site to switch its operating mode independently. Hence advanced strategies may use force control when in contact, and track a desired motion when not restricted by the environment.

## V. Wave Filtering

It is common for robot controllers to incorporate knowledge of the desired joint or endpoint acceleration, especially if they are to be used for tracking purposes. Such knowledge enables a prediction of the control torques needed to sustain the desired motion and, using feedforward components, allows considerable improvements in tracking performance to be achieved.

Providing the desired acceleration is typically straightforward if the desired motion is given *a priori* or generated by some external source without direct feedback to this source. Simple filtering of the signal produces a smooth motion with known derivatives. This can be done without any effects on stability, as the desired trajectory is generated in an "open-loop" fashion.

However, as used in teleoperation, force-reflection establishes a feedback connection to the motion-generating device. This

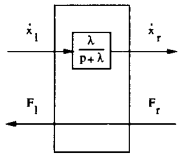


Fig. 12. Nonpassive filtering of a power variable.

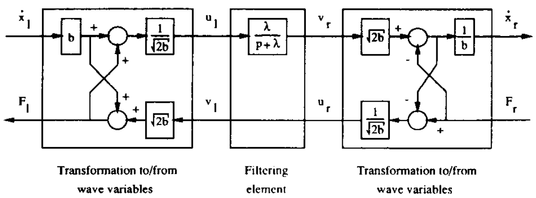



Fig. 13. Passive filtering of a wave variable.

closes an additional control loop around the system and may increase performance. It also introduces the stability issues inherent to any control system. In particular, filtering the motion signal as before adds significant phase-lag to the system and risks severe stability problems.

Using the passivity formulation, a filtering element within a closed-loop system can be interpreted as a 2-port element (shown in Fig. 12). The power flow into such an element is governed by

$$P = \dot{x}_l^T F_l - \dot{x}_r^T F_r = \left(\frac{1}{\lambda}\ddot{x}_r + \dot{x}_r\right)^T F_l - \dot{x}_r^T F_r = \frac{1}{\lambda}\ddot{x}_r^T F_l.$$

Without further information about the system, this power flow may well provide energy to the system. The filtering element is thus not passive and may destabilize the system. Note that the location of the filter within the element (i.e., in the forward or feedback path or both) does not affect the passivity arguments.

Noticing the similarities between pure time delays and slow filters, it seems reasonable that filtering too may be done passively within the wave-variable domain. Indeed, filtering a wave according to Fig. 13 retains passivity. Using the filter:

$$\dot{v}_r + \lambda v_r = \lambda u_l$$

provides the power flow:

$$\begin{aligned} P &= \frac{1}{2}u_l^T u_l - \frac{1}{2}v_l^T v_l + \frac{1}{2}u_r^T u_r - \frac{1}{2}v_r^T v_r \\ &= \frac{1}{2\lambda^2}\dot{v}_r^T \dot{v}_r + \frac{d}{dt}\frac{1}{2\lambda}v_r^T v_r \end{aligned}$$

which satisfies the passivity condition (1). Returning the filter equation to the power variables results in the relation:

$$\ddot{x}_r + 2\lambda \dot{x}_r = 2\lambda \dot{x}_l - \frac{1}{b}\dot{F}_r$$

$$F_l = F_r + b(\dot{x}_l - \dot{x}_r).$$

To compute the acceleration signal using the above filter requires knowledge of the force derivative $\dot{F}_r$. Equivalently, the force derivative can only be computed with knowledge of the acceleration. However, the acceleration signal is only required for accurate tracking controllers, which themselves should provide only minimal force reflection, as they cancel or simplify the dynamics of the system locally. In particular, the adaptive controller (Section VII) we shall propose to use for accurate slave control handles all uncertainties locally and only returns the applied contact force signals, which are proportional to the position error. Therefore the derivative of the force signal is known and the acceleration data can be obtained passively with the above wave filter.

A further important application of wave filters is in noise reduction. Performing the filtering directly in wave variables provides a passive and systematic way to reduce noise naturally present in the system. Such filters may be placed in either path within the element.

Finally, wave filters can also be utilized to provide frequency shaping of the perceived information. In mining operations (or, similarly, in oil drilling) for instance, it may be desirable to accentuate the vibrations felt by the operator that correspond to the transition from coal to rock. Similarly, teleoperated micro-surgical systems, besides allowing a surgeon to exercise his/her expertise at microscopic scales, could enhance critical aspects of the perceived contact forces. This represents another degree of flexibility for dynamic transformation or simplification, aimed at improving the overall performance of the man-machine system.

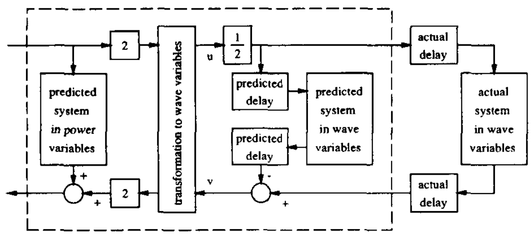
## VI. Wave Variable Predictors

Although teleoperation is a prime tool for dealing with unstructured environments, in many practical applications the user (or developer) may have reasonably good knowledge of the behavior of the remote system. This is particularly the case if advanced control schemes are used which provide consistent behavior regardless of operating conditions, as will be proposed in Section VII. Using this knowledge then allows the system to predict the remote response and include it into an immediate feedback loop to the operator. Such an immediate feedback scheme relieves the operator from the added difficulties of dealing with time delays.

Such ideas are found, for example, in *Smith predictors* [2], which are used in linear control theory to handle time delays within a control loop. Smith predictors simply feed back the predicted response immediately, as well as the prediction error after the real response has been measured. Stability of these systems, however, relies strongly on an accurate model of the remote dynamics and good cancellation of the system response, resulting in a negligible prediction error. The remaining predictions errors are simply treated as disturbances to which the controller must be robust. From a passivity perspective, dynamic cancellation provides equal amounts of energy to the system as is being dissipated by the real dynamics. This is obviously not passive and quite dangerous when the power dissipation is not estimated correctly.

As a fundamental assumption in our work has been to accept a wide variety of operating conditions governed by unknown passive environments, the immediate application of Smith predictors is not possible, since it cannot guarantee stability. Nevertheless, using the ideas of passivity and wave scattering, it is possible to include an immediate prediction feedback to the operator without destabilizing the system. This is achieved *if the prediction is itself computed in wave variables.* Fig. 14 shows a possible such setup.

Stability is maintained if the returning wave $v$ (representing the prediction error) is of magnitude less than that of the outgoing wave $u$, which commands both the prediction and actual system. This is achieved if the outgoing wave amplitude is reduced by one-half, as is seen in the Fig. 14. To compensate for the reduction, a simple passive unit-changing element may be inserted in the power variables before transformation.




Prediction Procedure
Fig. 14. Using stable prediction for immediate feedback to the operator.

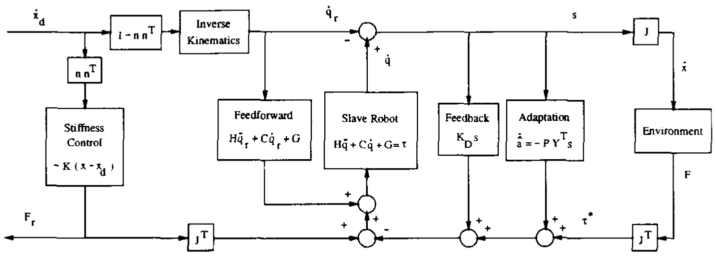



Fig. 15. The telerobot under adaptive control.

This system is always stable regardless of prediction errors and consequently has to modify the system dynamics, even in the case of perfect prediction. In such a case the returning wave is zero and the wave transformation mimics a damping element. In particular, the controller or operator must now provide energy to be dissipated in all three subsystems, including the real system as well as the immediate and delayed predictions.

This framework again provides much freedom in the choice of individual elements. For example, the choice of transmission scheme involves impedance matching and selection of force/position control. This leads to a wide variety of possible control structures, which can be tailored to the appropriate tasks at hand.

## VII. Adaptive Control of the Slave Manipulator

Since delays in the transmission severely restrict the dynamic control of the remote manipulator by an operator, it is important to provide consistent dynamic performance locally at the remote site in the face of uncertainties and varying operating conditions. This simplifies prediction of the system response, allowing "smarter" control approaches as described in Section VI, and enables the system to provide the operator with a simplified set of dynamics.

Dynamic compensation and transformation becomes especially important if the remote and local sites are of different sizes. Dynamic effects scale differently depending on their origin (e.g., inertial, friction, contact, viscous, or thermal forces), so that simple scaling of forces and motion will distort the dynamic behavior. Therefore to obtain desirable perceived dynamics, whether simplified, enhanced, or transformed, such scaling effects must be treated explicitly.

Adaptive control is well suited for providing dynamic transformations and can actually be treated in the same passivity framework used to analyze the communications. In essence, it can allow most of the dynamic complexities of the task to be factored out from the dynamics perceived by the operator. A simple globally convergent adaptive tracking controller was previously developed in [12]. In [7] and [8], we presented a passivity interpretation of this adaptive controller, including possible contacts to the environment. By introducing feedback of the applied virtual spring forces, this controller design can be implemented within the teleoperation system. Fig. 15 gives a complete diagram of the telerobot, including the adaptive controller.

A key element within the adaptive tracking controller is the use of feedforward compensation. By applying the torques necessary to sustain the desired motion, accurate tracking can be achieved. Note that this requires knowledge of the desired acceleration, which can be obtained using the filtering approach of Section V. The use of feedforward creates a passive element which maps any remaining applied torques to the tracking error $s$. Simply including a constant-gain feedback loop then corresponds to connecting an additional strictly passive element, and thus provides the asymptotic tracking convergence required.

Given the uncertainties involved in the control problem, the feedforward compensation will almost always include errors. The energy generated hereby can be canceled when using the correct parameter adaptation mechanism. Thus even with uncertainties, passivity is maintained and accurate motion control is achieved.

The final important aspect of the adaptive controller is the distinction between axes involving free motion and axes with restricted motion (which are perpendicular to any contact surfaces). This distinction allows precise motion to be achieved while still controlling the contact explicitly. Given the contact direction $\boldsymbol{n}$, which can be obtained from contact sensing as well as *a priori* knowledge, the desired motion is mapped into directions parallel to the surface for motion control, and perpendicular to the surface for contact control. The latter is performed by a stiffness controller, which uses a virtual spring to create the desired contact forces. The motion controller provides additional damping to establish a well-behaved contact. Note that in general the contact forces can be generated by any passive procedure, including a nonlinear spring. For instance, a constant contact force can be provided by using saturated virtual springs.

The applied forces, as provided by the stiffness controller, are reflected to the operator. They provide a good representation of the actual contact forces if the manipulator is easily back-driva-

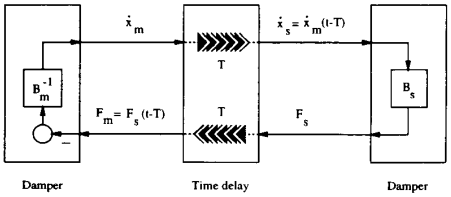



Fig. 16. Standard communications connecting two simple dampers.

ble. Note that this back-drivability assumption is fundamental to any force-reflecting operation and can be artificially enforced by using force sensors to drive a local-force feedback loop. Also note that reflecting data from a force sensor directly to the operator is not passive and should thus be avoided. Using the applied forces furthermore provides a smooth signal, since it eliminates sudden impact forces.

By using such a combination of adaptive tracking control and stiffness control, the remote system can reduce the workload for the operator. That is, as long as errors are caused by parametric uncertainty due to changing operating conditions, the adaptive controller will automatically provide the necessary actions by updating its model. However, if errors are generated by external contacts that cannot be included into the model, the information is passed to the operator in the form of the contact forces. The operator thus only sees a simplified set of dynamics and does not need to deal with the true nonlinear dynamics of the manipulator.

Thus the above control scheme enables the remote system to achieve stable contact with any passive environment, providing consistently high performance and simplified apparent dynamics while maintaining at all times the passivity properties of the overall teleoperation system.

## VIII. Concluding Remarks

This study show the richness and versatility that the passivity formalism may allow in the design of telerobotic systems. We believe that a precise understanding of the various trade-offs and optimizations involved presents great potential in the development of effective teleoperation or telepresence systems, which would best exploit the presence of the human operator while making full use of available robot control technology and computing power.

## Appendix

### Examples of Unstable Systems With Standard Communications

Let us illustrate the mechanisms of instability due to time-delays in standard communications.

Consider a system consisting of the standard communications with a time delay of $T$ connecting two simple gain elements (e.g., dampers), pictured in Fig. 16. The system is described by

$$\dot{x}_m(t) = -B_m^{-1}F_m(t), \qquad F_s(t) = B_s\dot{x}_s(t) \qquad \text{(A1)}$$

which determines the overall system dynamics as

$$\dot{x}_m(t) = -B_m^{-1}B_s\dot{x}_m(t-2T).$$

This system is unstable if the combined coefficient $B_m^{-1}B_s$ exceeds the value of one; i.e., if $B_s > B_m$. This can be viewed as a particular case of the *small gain theorem*, which states that a closed-loop system is stable if the $H_\infty$ norm of the loop gain is less than one. Therefore adding additional feedback gain (i.e., increasing the damping $B_s$) actually increases the danger of instability. However, the actual value of the time delay does not effect the stability of this particular system.

Using a passivity analysis, one can see that the communications system is indeed creating power, which drives the system unstable. In particular, substituting the damper equations (A1) into the power dissipation of the communications (7) while using $B_m$ as the gain $b$, leads to

$$\begin{aligned} P_{\text{diss}} &= \frac{1}{B_m}F_m^2(t) - \frac{1}{2B_m}(F_m - B_m\dot{x}_m)^2(t) \\ &\quad + B_m\dot{x}_s^2(t) - \frac{1}{2B_m}(F_s + B_m\dot{x}_s)^2(t) \\ &= -\frac{1}{B_m}F_m^2(t) + B_m\dot{x}_s^2(t) - \frac{1}{2B_m}(B_s + B_m)^2\dot{x}_s^2(t) \end{aligned}$$

so that after including the power provided to the two dampers

$$P = -\frac{1}{B_m}F_m^2(t) - B_s\dot{x}_s^2(t)$$

the total energy changes according to

$$\begin{aligned} \frac{d}{dt}E_{\text{total}} &= P - P_{\text{diss}} \\ &= \left[-B_s - B_m + \frac{1}{2B_m}(B_s + B_m)^2\right]\dot{x}_s^2(t) \\ &= \frac{B_s^2 - B_m^2}{2B_m}\dot{x}_s^2(t) \end{aligned}$$

which is positive, meaning that the energy grows unbounded and that the system is unstable, if $B_s > B_m$, as was seen before.

The above example is most extreme and perhaps physically not too intuitive. A more realistic example is obtained by replacing one of the dampers with a simple mass. This then corresponds to an attempt at reducing the motion of a mass while measurements and actuation are delayed by $T$. The new system is then governed by the equation:

$$m\ddot{x}_m(t) = -B\dot{x}_m(t-2T).$$

Again, such a configuration is unstable if the damping gain is chosen too large; more precisely if

$$\frac{B2T}{m} > \frac{\pi}{2}$$

which implies that the total time delay provides more than a 90° phase shift at the frequency of the first-order system. A simple way to obtain this result is to substitute a solution of the form:

$$\dot{x}_m(t) = e^{ct}\sin(\omega t)$$

into the system equation, which produces the following conditions:

$$c = -\frac{B}{m}e^{-2cT}\cos(2\omega T)$$

and

$$\omega = \frac{B}{m}e^{-2cT}\sin(2\omega T).$$

A periodic solution ($c = 0$) is obtained for $B2T/m = \pi/2$, and the gradient $dc/dB$ relating the exponential behavior of the system to the damping coefficient can be shown to be positive. Thus this linear system is unstable if the damping exceeds the critical value.


## Acknowledgment

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