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Bilateral teleoperation: An historical survey☆

Peter F. Hokayem*, Mark W. Spong

Coordinated Science Laboratory, University of Illinois, Urbana-Champaign, 1308 W. Main St., Urbana, IL 61801, USA

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Abstract

This survey addresses the subject of bilateral teleoperation, a research stream with more than 50 years of history and one that continues to be a fertile ground for theoretical exploration and many applications. We focus on the control theoretic approaches that have been developed to address inherent control problems such as delays and information loss. Exposure to several concurrent applications is provided, and possible future trends are outlined.

Keywords: Teleoperation; Robotic manipulators; Telerobotics; Robot control; Passivity; Passivity-based control; Scattering theory

1. Introduction

Over the past 50 years, a plethora of research has been targeted at understanding and overcoming pertinent problems in bilateral teleoperation. Since the mid 1940s, when the first master–slave teleoperator was built by Goertz, the field of teleoperation has passed through several stages from understanding the interaction between the human and robots to a mostly control theoretic arena. On the subject, there are two excellent surveys Sheridan (1989, 1993), in which the main focus is on supervisory control, human–machine interaction, and software-based teleoperation. In this survey we will direct our attention to the control theoretic aspect of the problem. In addition, teleoperation over the Internet, which began in the mid 1990s, has introduced new problems and is also addressed in this survey.

The prefix *tele* from Greek origin means *at a distance* and *teleoperation* naturally indicates operating at a distance. Thus teleoperation extends the human capability to manipulating objects remotely by providing the operator with similar conditions as those at the remote location (Fig. 1). This is achieved via installing a similar manipulator or joystick, called the *master*, at the human's end that provides motion commands to the *slave* which is performing the actual task. In a general setting, the human imposes a force on the master manipulator which in turn results in a displacement that is transmitted to the slave that mimics that movement. If the slave possess force sensors, then it can transmit or *reflect* back to the master reaction forces from the task being performed, which enters into the input torque of the master, and the teleoperator is said to be controlled *bilaterally*. Although reflecting the encountered forces back to the human operator enables the human to rely on his/her tactile senses along with visual senses, it may cause instability in the system if delays are present in the communication media. This delay-induced instability of force reflecting teleoperators has been one of the main challenges faced by researchers.

From a control theoretic point of view the main goals of teleoperation are twofold:

Stability: Maintain stability of the closed-loop system irrespective of the behavior of the operator or the environment.

Telepresence: Provide the human operator with a sense of telepresence, with the latter regarded as *transparency* of the system between the environment and the operator.

These tasks are generally conflicting. However, satisfying these requirements extends the capabilities of the human by scaling her/his power into manipulating huge objects, as in outer

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* Corresponding author. Tel.: +1 217 333 6721; fax: +1 217 244 1653.
E-mail addresses: hal@uiuc.edu (P.F. Hokayem), mspong@uiuc.edu (M.W. Spong).

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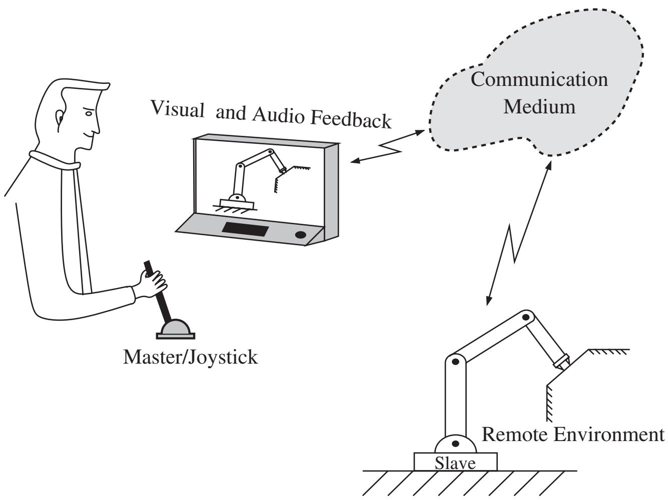

Fig. 1. Bilateral teleoperation.

space construction, or performing delicate tasks, as in microsurgery; thus projecting his/her expertise into distant locations.

Several complications arise when studying teleoperated systems since the communication medium (wired or wireless) contributes substantially to the complexity of the overall system and introduces distortion, delays, and losses that impact stability and performance. These issues have motivated the control theoretic research in teleoperation over the past decades.

1.1. Historical time line

The time line of teleoperation originates in the mid 1940s, according to Sheridan (1989), when Goertz built the first mechanically controlled master slave teleoperator. An improved version of the latter design was reported in Goertz (1954a,b), and an electrical force reflecting position servomechanism was utilized in 1954, to achieve mechanical separation of the master and slave. During the early 1960s an increased interest in the subject led to several experiments to try to understand the effects of delay in teleoperation (Ferrell, 1965; Sheridan & Ferrell, 1963), where reflecting the force back to the master was tested under the effects of delays in communication (Ferrell, 1965). Supervisory control was developed to address the problem of delays (Ferrell & Sheridan, 1967), and inspired a long line of research in devising new teleoperation-oriented software languages (Fong, Dotson, & Bejczy, 1986; Lee, Bekey, & Bejczy, 1985; Madni, Chu, & Freedy, 1983; Sato & Hirai, 1987), and visual enhancements using predictive display (Bejczy & Kim, 1990; Bejczy, Kim, & Venema, 1990; Buzan & Sheridan, 1989; Fong et al., 1986; Hirzinger, Heindl, & Landzettel, 1989; Stark et al., 1987), that minimize communication exchange between the master and slave sides of the network.

Beginning in the mid 1980s, more advanced control theoretic methods started to appear, such as Lyapunov-based analysis (Miyazaki, Matsubayashi, Yoshimi, & Arimoto, 1986) and internal virtual model (Furuta, Kosuge, Shiote, & Hatano, 1987). In the late 1980s and early 1990s, network theory came into play through impedance representation (Raju, Verghese, & Sheridan, 1989), hybrid representation (Hannaford & Fiorini, 1988), scattering theory and passivity-based control (Anderson & Spong, 1989b; Niemeyer & Slotine, 1991a). The passivity-based approach paved the way for stable time-delayed teleoperation. Research addressing transparency was presented in Lawrence (1992), Yokokohji and Yoshikawa (1994) that dictated the necessity of two-way transmission of force and velocity. Several results using $\mathscr{H}_\infty$ appeared in the mid 1990s (Leung & Francis, 1994; Leung, Francis, & Apkarian, 1995; Sano, Fujimoto, & Tanaka, 1998), during the same time when the Internet began to be used for communication. Packet switched networks presented the already established time-delay analysis with difficulties due to randomly varying delays, discrete-time exchange of data and loss of information. As a consequence, earlier delay-related results were adapted to the new setting (Lozano, Chopra, & Spong, 2002; Niemeyer & Slotine, 1997a,b), as well as to discrete-time setting (Berestesky, Chopra, & Spong (2004); Kosuge & Murayama (1997); Ryu, Kwon, & Hannaford (2002); Secchi, Stramigioli, & Fantuzzi (2003b); Yokokohji, Imaida, & Yoshikawa (2000)), and information loss (Berestesky et al., 2004; Secchi et al., 2003b).

The methods mentioned above found their way to several applications in handling radioactive material (Clement, Vertut, Fournier, Espiau, & Andre, 1985; Wang & Yuan, 2004), operating unmanned underwater vehicles (Funda & Paul, 1991; Madni et al., 1983; Yoerger & Slotine, 1987; Yoerger, Newman, & Slotine, 1986), space robotics (Bejczy & Szakaly, 1987; Hirzinger, 1987; Hirzinger, Brunner, Dietrich, & Heindl, 1993; Hirzinger et al., 1989; Imaida, Yokokohji, Doi, Oda, & Yoshikwa, 2004; Jenkins, 1986; Lee et al., 1985; Yoon et al., 2004), telesurgery (Funda, Taylor, Eldridge, Gomory, & Gruben, 1996; Madhani, Niemeyer, & Salisbury, 1998), and recently teleoperation of mobile robots (Diolaiti & Melchiorri, 2002; Hong, Lee, & Kim, 1999; Kawabata, Ishikawa, Asama, & Endo, 1999; Lim, Ko, & Lee, 2003; Makiishi & Noborio, 1999; Rösch, Schilling, & Roth, 2002; Schilling & Roth, 1999).

The material in this paper is categorized into four sections. Section 2 addresses approaches such as supervisory control that were dominant until the early 1990s. Sections 3 and 4 put teleoperation on control-theoretic grounds, while the former concentrates on the so-called passivity-based control schemes. Finally, Section 5 provides an overview of some of the numerous applications of teleoperation.

2. The earliest approaches

2.1. Initial experiments

In the early 1960s, Sheridan and Ferrell (1963) and Ferrell (1965) conducted some simple manipulation experiments to determine the effect of time delays on the performance of human operators in teleoperated manipulators. The objective was to quantify the total time required to accomplish a certain prespecified task. It was noticed that whenever delays were introduced in the communication loop, the human operator responded by adopting a *move-and-wait* strategy to insure that the task was completed. Such a move-and-wait strategy is comprised of initiating a control move and then waiting to see the response of the distant robot; then, initiating a corrective move and waiting again to realize the delayed response of the distant system and the cycle repeats until the task is accomplished.

Let us define $N(I)$ to be the number of individual moves initiated by the operator according to the move-and-wait strategy. The number $N(I)$ depends only on the task difficulty and is independent of the delay value according to experiments (Sheridan & Ferrell, 1963). Consequently, the completion time, $t(I)$, of a certain task can be calculated based on the value $N(I)$ as follows:

$$t(I) = t_{\mathrm{r}} + \sum_{i=1}^{N(I)} (t_{mi} + t_{wi}) + (t_{\mathrm{r}} + t_d)N(I) + t_{\mathrm{g}} + t_d, \tag{1}$$

where t_{r} is the human's reaction time, t_{mi} are the movement times, t_{wi} are the waiting times after each move, t_{g} is the grasping time and t_d is the delay time introduced into the communication channel.

The above experiments resulted in a twofold conclusion that the completion time is linear with respect to the induced delay in the loop, and the human operator performed in a 'stable' fashion, i.e. initiated well-behaved movement sequence in accordance with the move-and-wait strategy.

2.2. Supervisory control

As seen in (1), the completion time for a specific task depends linearly on the delay factor in the control loop; hence, the larger the delay, the larger the completion time. A feasible solution to circumvent this problem is to allow the type of commands issued by the operator to be of a *supervisory* nature (Ferrell & Sheridan, 1967). Depending on the task difficulty and the autonomy that the remote controller possesses, the supervision could be either of *analog* or *symbolic* nature; the first accomplishes direct correspondence between the supervisor's commands and those of the remote manipulator, while the latter issues high level linguistic commands that the local controller of the manipulator interprets as subtasks to perform. Naturally in this setting, the remote manipulator is given more 'intelligence' to complete the small subtasks autonomously. The state-space formulation of the supervisory computer language (Whitney, 1969), presented the supervisory approach from an optimization point of view by constructing a discrete-time state space and applying search techniques to achieve optimal performance of tasks. This approach ignores the manipulation dynamics and concentrates on the static geometric aspect of the problem, that is the position of the manipulator, the manipulated object, and possible obstacles.

2.3. Software-based teleoperation

The advancement in microprocessor design during the 1970s and until the early 1990s geared the teleoperation research towards exploiting the constantly increasing computational power to achieve supervision at a higher level (Fong et al., 1986; Lee et al., 1985; Madni et al., 1983; Paul, Lindsay, & Sayers, 1992; Sato & Hirai, 1987), allowing the human operator to issue high level commands to the remote manipulator. A special programming language that implements supervisory control was made available as reported in Madni et al. (1983), along with visual and force feedback from the remote manipulator and environment. The programmed language could be broken down into primitive commands that do not require any input from the human operator, such as *close end-effector*, and variable commands which require the user's input of points or a complete specification of the trajectory, such as *move from point A to point B*. Moreover, complex tasks could be performed by chaining the primitive and variable commands.

Many extensions of supervisory control have appeared in which virtual objects are introduced to compensate for the operator's inability to visualize the whole space ahead using the slave-mounted camera due to objects blocking its view point (Park & Sheridan, 1991).

2.3.1. Modular software

In order to test the behavior of teleoperators under various conditions, the need to build a modular structure was realized in Lee et al. (1985). With such a structure the interactions between the operator and the machine, the implications of force feedback, and enhancements in visual display could be achieved as the software settings changed online. The vision aspect was studied and several Cartesian transformations were utilized to change between references frames of the display, controller, manipulator, and cameras.

A modular hardware and software system was also proposed in Fong et al. (1986) that allowed the operator to choose between various control modes and provides a virtual model of a manipulator on which to test the developed system. Flexibility is provided for the operator to choose between issuing position or velocity commands for the manipulator to follow, placing the teleoperated master–slave system under unilateral or bilateral control, or using supervisory high level control. Moreover, a virtual environment model is realized in order to test the proposed new modular system with time-delays without operating the actual manipulator since it could be unstable under delays. Delays in the control loop motivated the development of *predictive display* (Bejczy & Kim, 1990; Bejczy et al., 1990; Buzan & Sheridan, 1989; Fong et al., 1986; Hirzinger et al., 1989; Stark et al., 1987), which allows the operator to view the response of the system before it actually happens and hence avoid possible collisions.

Further improvements were suggested in Sato and Hirai (1987), namely the *software jig* and teaching mode of the teleoperator. The software jig refers to constraints implemented in software, which facilitate the task of the human operator; for example, carrying a glass of water requires no orientation change along the *x*- and *y*-axes and is a task that can be handled by software. Moreover, introducing a teaching mode module allows the user to achieve repeatability of a task performed earlier by calling the subroutine that performs what was previously stored in memory.

Until the late 1980s, very few results considered the control theoretic point of view from which we outline the following:

Lyapunov analysis: In Miyazaki et al. (1986) the position tracking problem is solved via a Lyapunov-like analysis for the delay-free teleoperator.

Shared compliant control (*SCC*): (Hannaford & Kim, 1989) This architecture *complies* with environment once in contact in order to ease the otherwise stiff contact, which could inject oscillations in the system. Low-pass filtering of the slave's response once in contact with a hard surface could damp the possible oscillations (Kim, 1990), and stability of such a configuration was analyzed using Bode plots. Other instances of this method can be found in Bejczy and Kim (1990), Kim (1990) and Kim, Hannaford, and Fejczy (1992).

3. Passivity-based teleoperation

Mathematically, we think of a teleoperator as comprised of two robotic subsystems a *master* and a *slave* that exchange signals (positions, velocities and/or forces); in which the slave tries to mimic the behavior of the master which in turn takes into account the input torques from the slave. A linear model of master/slave system can be written as

$$(\mathrm{L}):\begin{cases} M_m\ddot{x}_m + B_m\dot{x}_m = f_m + f_{\mathrm{h}},\\ M_s\ddot{x}_s + B_s\dot{x}_s = f_s - f_{\mathrm{e}},\end{cases}$$

where $x_* \in \mathbb{R}^n$ ($* = m$ or s) are the generalized coordinates, $f_* \in \mathbb{R}^n$ are the (generalized) input forces, M_* is a positive inertia matrix, B_* is a damping matrix and f_{h}, f_{e} correspond to the external forces exerted by human operator and the environment, respectively.

A more detailed nonlinear model can be written using Lagrange's equations as

$$(\mathrm{NL}):\begin{cases} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m = f_m + f_{\mathrm{h}},\\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s = f_s - f_{\mathrm{e}},\end{cases}$$

where M_* is the inertia matrix, and the matrix $C(x_*,\dot{x}_*)$ is comprised of Coriolis and centrifugal terms. The nonlinear equations of motion (*NL*) possess several important structural properties (Spong, Hutchinson, & Vidyasagar, 2005) of which we will utilize the following:

(PD): $M_* = M_*^{\mathrm{T}}$ is positive definite,
(SS): $\dot{M}_* - 2C_*$ is skew symmetric.

Passivity theory is an input–output property of dynamical systems that has its origins in network theory and is concerned primarily with the exchange of energy between interconnected systems (Desoer & Vidyasagar, 1975).

Definition 1. A dynamical system given by

$$\dot{x} = f(x,u),$$
$$y = h(x,u)$$

is said to be *passive* if there exists a continuously differentiable semidefinite scalar function $V(x):\mathbb{R}^n \to \mathbb{R}$ (termed the storage function) such that

$$\dot{V} \leqslant u^{\mathrm{T}}y \quad \left(\equiv \int_0^t u^{\mathrm{T}}(\eta)y(\eta)\,\mathrm{d}\eta \geqslant V(t) - V(0)\right)$$

and *lossless* if

$$\dot{V} = u^{\mathrm{T}}y \quad \left(\equiv \int_0^t u(\eta)^{\mathrm{T}}y(\eta)\,\mathrm{d}\eta = V(t) - V(0)\right).$$

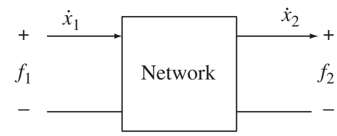

Fig. 2. Two-port network.

Proposition 2. *Given the properties* (PD) *and* (SS), *and assuming that the human and environment are passive, i.e.* $\int_0^t [f_{\mathrm{h}}^{\mathrm{T}}(\eta)\dot{x}_m(\eta) - f_{\mathrm{e}}^{\mathrm{T}}(\eta)\dot{x}_s(\eta)]\,\mathrm{d}\eta \geqslant 0$, *then the system* (*NL*) *with input* $[f_m^{\mathrm{T}}, f_s^{\mathrm{T}}]^{\mathrm{T}}$ *and output* $[\dot{x}_m^{\mathrm{T}},\ \dot{x}_s^{\mathrm{T}}]$ *is passive with respect to the storage function*

$$V = \frac{1}{2}\begin{bmatrix}\dot{x}_m\\ \dot{x}_s\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}M_m & 0\\ 0 & M_s\end{bmatrix}\begin{bmatrix}\dot{x}_m\\ \dot{x}_s\end{bmatrix}.$$

Therefore, we can look at the system (*NL*) as a lossless system by taking forces as inputs and velocities as outputs, and studying energy exchange occurring (a) within the teleoperator and (b) with the external world, i.e. human and remote environment. This is particularly useful since we know that a series cascade of passive two-ports is passive (with respect to the remaining open ports), and a series cascade of a two-port with a one-port network is also passive (with respect to the remaining open port). Moreover, we know that passivity leads to establishing the stability of the overall system by taking as a Lyapunov function the sum of storage functions of all the constituent blocks. Therefore, assuming that the environment and human operator are passive, if we can establish that the teleoperator is passive then we can guarantee passivity of the closed-loop system. Having this insight of the usefulness of passivity in the teleoperation setting, we proceed to describe various passivity-based approaches that have appeared in the literature.

3.1. 2-Port networks

In the late 1980s, it was observed that a teleoperator system, comprised of a master and slave with their corresponding controllers, residing between the human operator and the environment can be modeled as a two port network (Buzan & Sheridan, 1989; Hannaford, 1989a,b; Hannaford & Fiorini, 1988) for which analysis tools are readily available.

Let us consider the two port network illustrated in Fig. 2, with external signals being efforts and flows which correspond to voltages and currents in electric circuits or forces and velocities in mechanical systems, respectively.

The behavior of this network can be captured using different matrix representations such as impedance—$Z(s)$

(Raju et al., 1989), relating forces to velocities, or hybrid—$H(s)$ (Hannaford, 1989a,b), relating mixed force-velocity vectors to mixed force-velocity vectors. Each of these representations is useful depending on the available sensed signals and control inputs.

3.2. Impedance matrix

Assuming that we have flows as inputs on both sides of the two port network, then an impedance representation of a PD-controlled[1] master–slave network can be utilized to relate velocities to forces through an impedance matrix as

$$\begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \underbrace{\begin{pmatrix} z_m(s) - c_{11}(s) & -c_{12}(s) \\ -c_{21}(s) & z_s(s) - c_{22}(s) \end{pmatrix}}_{Z_{\mathrm{cl}}(s)} \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix},$$

where z_* are the impedances that characterize the master and slave. Notice that the controller $(c_{ij}, i, j = 1, 2)$ affects all the entries of the controlled impedance matrix $Z_{\mathrm{cl}}(s)$, which allows us to manipulate its elements to achieve passivity of the network by requiring $Z_{\mathrm{cl}}(s)$ to be a positive real transfer matrix.

3.3. Hybrid matrix

On the other hand, if force sensing is available at the slave's side, then the following is an alternative hybrid representation (Hannaford, 1989a):

$$\begin{pmatrix} f_1(s) \\ -\dot{x}_2(s) \end{pmatrix} = \underbrace{\begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix}}_{H(s)} \begin{pmatrix} \dot{x}_1(s) \\ f_2(s) \end{pmatrix}, \tag{2}$$

where $H(s)$ is the *hybrid matrix*. Moreover, the elements of this matrix have a natural physical interpretation

$$H(s) = \begin{pmatrix} Z_{\mathrm{in}} & \mathrm{ForceScaling} \\ \mathrm{VelocityScaling} & Z_{\mathrm{out}}^{-1} \end{pmatrix}.$$

Hence, we would like to obtain an ideal $H(s)$ matrix that achieves *kinesthetic* feedback between the environment and the human operator. That is, ideally we would like to have a zero input impedance and infinite output impedance which would result in a ideal behavior given by

$$H_{\mathrm{ideal}}(s) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \tag{3}$$

A method for obtaining this ideal behavior of the 2-port network was proposed in Hannaford (1989a) that involves estimating and transmitting to the opposite side the environment and human operator dynamics. Another approach was proposed in Strassberg, Goldenberg, and Mills (1992a,b) via feedback linearization of the equations of motion; then, two controllers are designed for the master, one depending on local position and another on force error between the two manipulators. Another two compensators, one depending on velocity difference and another on local force, provide the control input signals for the slave manipulator. This architecture achieves transparency condition (3) by design of the latter four compensators.

As will be seen later this hybrid representation has become the basis for several theoretical contributions such as the scattering approach and 4-channel model.

[1] PD stands for proportional-derivative and not the (PD) property discussed earlier.

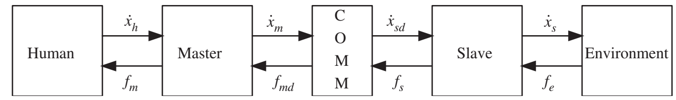

Fig. 3. Teleoperator.

3.4. Scattering approach

Before 1988, the problem of time-delay induced instability in bilateral teleoperation was the major impediment inhibiting further progress. Anderson and Spong (1989a,b, 1988), introduced the notion of scattering variables, which were well-known in transmission line theory, to the problem of bilateral teleoperation. In this section we outline the procedure in Anderson and Spong (1989b) that renders the teleoperator system passive. The bilateral teleoperator considered henceforth is depicted in Fig. 3. Such a system can be viewed as a series cascade of 1- and 2-port networks with an effort–flow pair being exchanged at each port (the force–velocity pair in the case of mechanical systems). The relationship between the forces and velocities at all ports can be represented, in the LTI case as mentioned earlier, by the hybrid matrix (2) which enters into the definition of the *scattering operator*.

Definition 3. The scattering operator is defined in terms of an incident wave $(f(t) + \dot{x}(t))$ and a reflected wave $(f(t) - \dot{x}(t))$ as: $f(t) - \dot{x}(t) = S(f(t) + \dot{x}(t))$.

In the case of a 2-port network (2), the scattering matrix in the frequency domain can be represented in terms of the hybrid matrix by simple loop transformation

$$S(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} (H(s) - I)(H(s) + I)^{-1}. \tag{4}$$

In order to guarantee passivity, the scattered wave cannot have energetic content greater than the incident wave, hence with respect to the scattering operator S:

Theorem 4 (*Anderson & Spong, 1989b*). *An n-port system is passive if and only if $\|S(\mathrm{j}\omega)\|_\infty \leqslant 1$ of the corresponding scattering matrix.*

The above theorem can be inferred from the following argument in terms of the input power and output power to the 2-port network. Let f and $\dot{x}$ be the force and velocity vectors, respectively, and define P_{in} and P_{out} to be the input and output power, respectively, then the power difference is given by

$$\Delta P = P_{\mathrm{in}} - P_{\mathrm{out}} = f^{\mathrm{T}}\dot{x} = \left(\frac{f+\dot{x}}{2}\right)^{\mathrm{T}}\left(\frac{f+\dot{x}}{2}\right) - \left(\frac{f-\dot{x}}{2}\right)^{\mathrm{T}}\left(\frac{f-\dot{x}}{2}\right).$$

Defining the scattering variables $s_+ = ((f+\dot{x})/2)^{\mathrm{T}}$ and $s_- = ((f-\dot{x})/2)$, then ΔP can be rewritten in terms of the scattering variables as

$$\Delta P = s_+^{\mathrm{T}} s_+ - s_-^{\mathrm{T}} s_- = s_+^{\mathrm{T}}(I - S^{\mathrm{T}}S)s_+ \tag{5}$$

and requiring that the power difference be nonnegative imposes the condition on the maximum singular value of the scattering matrix, i.e.

$$\|S\|_\infty = \bar{\sigma}(S^{\mathrm{T}}(\mathrm{j}w)S(\mathrm{j}w)) \leqslant 1.$$

Of course, the rational behind Theorem 4 is that the power of the wave incident upon the two port network cannot be magnified, at best the reflected (scattered) wave carries the same power.

3.4.1. Constant time delays

The scattering formulation in Section 3.4 can be used to develop control laws that guarantee stability for systems with constant delays. Consider the system (L) transmitting signals via a constant delay T with the following control law:

$$f_m(t) = -f_{md}(t) = -f_s(t-T),$$
$$f_s(t) = K_s \int (\dot{x}_{sd}(t) - \dot{x}_s(t))\,\mathrm{d}t + B_{s2}(\dot{x}_{sd}(t) - \dot{x}_s(t)), \tag{6}$$

where $f_s(t)$ is called the *coordinating torque*, and $\dot{x}_{sd}(t) = \dot{x}_m(t-T)$.

The above signals result in a hybrid matrix composed of pure delay elements that render the norm of the scattering operator as $\|S\|_\infty = \infty$, which is not passive. Therefore, the pure delay communication channel generates energy which possibly destabilizes the teleoperator. This problem can be remedied by emulating the behavior of transmission lines via adopting the scattering formulation that *passifies* the communication channel

$$f_{md}(t) = f_s(t-T) + Z_0(\dot{x}_m(t) - \dot{x}_{sd}(t-T)),$$
$$\dot{x}_{sd}(t) = \dot{x}_m(t-T) + Z_0^{-1}(f_{md}(t-T) - f_s(t)), \tag{7}$$

where Z_0 is characteristic impedance inherent to transmission lines theory, that we can view as the ratio of a transformer placed between forces and velocities, that makes their values comparable. Note that all the signals in (7) could be vector-valued in which case Z_0 would be a matrix (Anderson & Spong, 1989a). This control scheme results in the scattering matrix

$$S(s) = \begin{pmatrix} 0 & \mathrm{e}^{-sT} \\ \mathrm{e}^{-sT} & 0 \end{pmatrix}$$

which has norm $\|S\|_\infty = 1$; hence, we have a passive communication channel by Theorem 4. Moreover, as we discussed earlier, we can infer the stability of the teleoperator for all passive environments and a passive behavior by the human operator.

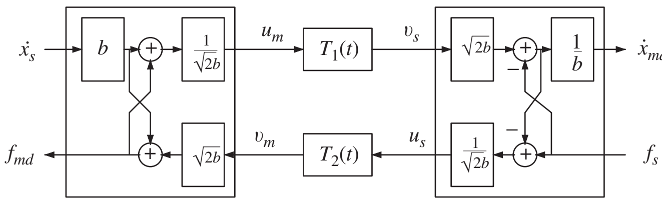

Fig. 4. Wave variables.

Such formulation achieves velocity and force matching. However, position mismatch or drift between the master the slave positions remains a difficult problem. We will discuss this problem in later sections (Anderson & Spong, 1989a).

3.4.2. Scaling

In many applications such as telesurgery or telemanipulation of large objects, it is required that the power transmitted from one side of the teleoperator to the other be scaled to enable the human operator to handle the mismatch with the environment adequately, an issue discussed in Colgate (1991). Assume that the environment and the human operator are each passive and can be represented by scattering matrices S_{h} and S_{e}, respectively. Then a compact representation can be given as

$$S_{\mathrm{he}}(s) = \begin{pmatrix} S_{\mathrm{h}} & 0 \\ 0 & S_{\mathrm{e}} \end{pmatrix}, \tag{8}$$

where $\|S_{\mathrm{he}}(s)\|_\infty \leqslant 1$ (due to the passivity assumptions). The teleoperator between the human and the environment is also represented by the scattering matrix, which subsumes the dynamical models of the master and slave and possible power and impedance scaling,

$$S_{ms}(s) = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix}$$

then the passivity of $S_{ms}(s)$ can be determined as before.

A conceptually similar approach was undertaken in Kosuge, Itoh, and Fukuda (1996) in the time-domain. The interaction with the environment is scaled by defining the interaction velocity and forces as

$$\dot{x}_s \doteq c_v \dot{x}_{\mathrm{e}}, \quad f_{\mathrm{e}} \doteq c_f f'_{\mathrm{e}},$$

where c_v and c_f are scaling factors and $\dot{x}_{\mathrm{e}}$ and $\dot{f}'_{\mathrm{e}}$ are the effective power variables that are applied and sensed from the environment, respectively. Clearly, these definitions only scale the instantaneous power but do not alter its sign, that is $f_{\mathrm{e}}^{\mathrm{T}}\dot{x}_{\mathrm{e}} = c_v c_f (f'_{\mathrm{e}})^{\mathrm{T}}\dot{x}_{\mathrm{e}}$, and hence passivity of the environment is preserved.

3.5. Wave variables

A conceptually similar formulation to the scattering formulation appeared in Niemeyer and Slotine (1991a), the so-called *wave variables formulation*. As seen in Fig. 4, instead of exchanging as reference signals the power variables $\dot{x}_m$ and f_s the wave variables are transmitted u_m and u_s, which are given by

$$u_m(t) = \frac{1}{\sqrt{2b}}(f_{md}(t) + b\dot{x}_m(t)),$$
$$u_s(t) = \frac{1}{\sqrt{2b}}(f_s(t) - b\dot{x}_{sd}(t)), \tag{9}$$

where f_{md} and $\dot{x}_{sd}$ are the received power signals on the master and slave side, respectively. This formulation is identical to the scattering formulation, with b being the characteristic impedance of the transmission line. As in (5) the total power flow in the communication channel can be written equivalently in terms of wave variables

$$\begin{aligned} P(t) &= f_{md}^{\mathrm{T}}(t)\dot{x}_m(t) - f_s^{\mathrm{T}}(t)\dot{x}_{sd}(t) \\ &= \tfrac{1}{2}(u_m^{\mathrm{T}}(t)u_m(t) - v_m^{\mathrm{T}}(t)v_m(t)) \\ &\quad + \tfrac{1}{2}(u_s^{\mathrm{T}}(t)u_s(t) - v_s^{\mathrm{T}}(t)v_s(t)), \end{aligned} \tag{10}$$

where v_m and v_s are the received wave signals and the reference signals on both sides of the channel are derived as

$$f_{md}(t) = b\dot{x}_m(t) + \sqrt{2b}v_m,$$
$$\dot{x}_{sd}(t) = \frac{1}{b}(\sqrt{2b}v_s(t) - f_s(t)).$$

Note that in the last equation we have the symmetry in defining the wave variables (9) in the sense that given any two of the power and wave variables, the remaining variables can be easily derived. Moreover, the master and slave can be put under force or velocity reference control.

When the channel is comprised of constant time delays ($T_i(t) = T_i$, $i = 1, 2$), the wave formulation gives the same transformation in (7), and the passivity analysis can be alternatively performed in time domain. From (10) we can see that

$$E(t) = \frac{1}{2}\left\{\int_{t-T}^{t}(u_m^{\mathrm{T}}(\eta)u_m(\eta) + u_s^{\mathrm{T}}(\eta)u_s(\eta))\,\mathrm{d}\eta\right\} \geqslant 0 \tag{11}$$

and hence, the channel is passive.

Due to the intrinsic passivity of the wave formulation, several control strategies are made possible in the wave domain that otherwise cause the loss of passivity when performed directly in the power variables domain. For example placing a passive filter inside the wave variables domain does not destroy the passivity of the communication channel, a fact exploited in Munir and Book (2001a,b) through the use of the Smith predictor.

Consider a predictor inside the communication channel at the master's side given by

$$G_p(s) = (1 - \mathrm{e}^{s(T_1+T_2)})\hat{G}_s(s),$$

where $\hat{G}_s(s)$ is an estimate of the slave model and T_1, T_2 are known constant delays in the forward and backward paths, respectively. A Smith predictor is used to overcome constant known delays and provide a prediction of the wave variable $v_p = G_p(s)u_m$ that is added to the transmitted and delayed wave variable u_s in order to provide a corrected variable v_m at the master's side. This is performed while monitoring the energy content of the predicted wave so that

$$\int_0^t u_s^{\mathrm{T}}(\eta)u_s(\eta)\,\mathrm{d}\eta \geqslant \int_0^t v_m(\eta)^{\mathrm{T}}v_m(\eta)\,\mathrm{d}\eta, \quad \forall t \geqslant 0 \tag{12}$$

thus retaining passivity of the channel. Due to sensitivity of the Smith predictor to initial condition mismatches between $G_s(s)$ and $\hat{G}_s(s)$, a Kalman filter was utilized to provide an estimate of the state of the right-hand side plant predicted ($T_1 + T_2$) seconds forward in time. Define the following sum:

$$v_t(t) = u_s(t - T_2) + v_p(t) \doteq v_a(t) + v_p(t)$$

then the actual value of v_m is calculated as

$$v_m(t) = c_1(1 - \mathrm{e}^{-c_2 E_{\mathrm{r}}(t)})\int_0^t (v_t(\eta) - v_m(\eta))\,\mathrm{d}\eta,$$

where E_{r} is an energy 'reservoir' that monitors the passivity condition (12) and is given by

$$E_{\mathrm{r}}(t) = \int_0^t (v_a^{\mathrm{T}}(\eta)v_a(\eta) - v_m^{\mathrm{T}}(\eta)v_m(\eta))\,\mathrm{d}\eta \geqslant 0.$$

Thus, the regulator ensures that the passivity is enforced after adding the correction variable $v_p(t)$. The variable delay case was treated in Munir and Book (2001a), where a correction term were added to u_m that compensates for small variations in the nominal delays, similar to that given in Niemeyer and Slotine (1997a). Also see similar utilization of the Smith predictor in Ganjefar, Momeni, and Janabi-Sharifi (2002).

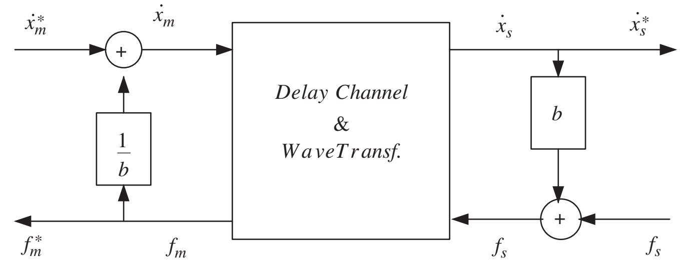

Fig. 5. Impedance matching.

3.5.1. Matching impedances

In the context of transmission line theory, it is well known if the load that terminates the line has a different impedance than the characteristic impedance of the transmission line then wave reflections occur. In the case of bilateral teleoperation, such reflections degrade the performance of the system. This led to the introduction of impedance-matching elements b at each end of the communication channel (Fig. 5). Note that this is the basic setting that can be adapted to impedance matching when the slave manipulator is placed under impedance or force control as discussed in Niemeyer and Slotine (1991b).

Arguing that impedance matching elements at both sides of the communication block affects position tracking, Benedetti, Franchini, and Fiorini (2001) removed the matching element on the masters side, which results in a smaller position drift given by

$$x_m^*(t-T) - x_s(t) = \frac{1}{2b}\int_{t-2T}^{t} f_s^*(\eta)\,\mathrm{d}\eta$$

as compared to the drift that results from using the matching elements on both side of the channel given by

$$x_m^*(t-T) - x_s(t) = \frac{1}{b}\int_{0}^{t} f_s^*(\eta)\,\mathrm{d}\eta + x_s(t).$$

It is also argued that an increase in the value of b results in a smaller position drift. Of course this comes at the expense of extra damping which could affect negatively the performance of the system.

3.6. Geometric scattering

The exposition in Stramigioli, van der Schaft, Maschke, and Melchiorri (2002) lifts the presentation of the scattering operator in Section 3.4 into a geometric setting, and presents the results in Sections 3.4 and 3.5 in a compact form. Consider the vector space $\mathscr{V}$ of flows (voltages, forces) and its dual $\mathscr{V}^*$ the space of efforts (currents, velocities) that form a Cartesian product space given by

$$\mathscr{D} = \mathscr{V} \times \mathscr{V}^*,$$

where $(f, e) \in \mathscr{D}$. Then, on the space $\mathscr{D}$, there exists a unique way (for each given impedance Z) to decompose it into two eigensubspaces as

$$\mathscr{D} = \mathscr{S}_Z^+ \oplus \mathscr{S}_Z^-,$$

where $\mathscr{S}_Z^+$ and $\mathscr{S}_Z^-$ are subspaces of the incident and reflected scattered variables, respectively, and we have the following power decomposition theorem (notice that this gives the geometric counterpart of the result in (5)).

Theorem 5 (*Stramigioli et al., 2002*). *$\forall (f, e) \in \mathscr{D}$ and any $Z = Z^{\mathrm{T}} > 0$ the following holds*:

$$\langle e, f\rangle = \tfrac{1}{2}\,\|s_Z^+\|_+^2 - \tfrac{1}{2}\|s_Z^-\|_-^2,$$

where $s_Z^+ \in \mathscr{S}_Z^+$, $s_Z^- \in \mathscr{S}_Z^-$, $(f, e) = s_Z^+ + s_Z^-$, and $\|.\|_+$ and $\|.\|_-$ are induced inner products on $\mathscr{S}_Z^+$ and $\mathscr{S}_Z^-$, respectively.

More general conditions for the cases of perfect and imperfect impedance matching can also be found in Stramigioli et al. (2002).

3.7. Teleoperation over the Internet

Teleoperation over the internet began in the mid 1990s (Goldberg et al., 1995) and has been an active research area since then (Brady & Tarn, 1998, 2001; Elhaij, Hummert, Xi, Fung, & Liu, 2000; Oboe, 2001, 2003; Xi & Tarn, 1999, 2000). Communicating information across a packet-switched network results in random, time-varying delays that can reach very high values and eventually lead to loss of packets. Furthermore, the need to deal with discrete-time stability arises. As a result the performance of the teleoperated system may deteriorate drastically and may possibly become unstable.

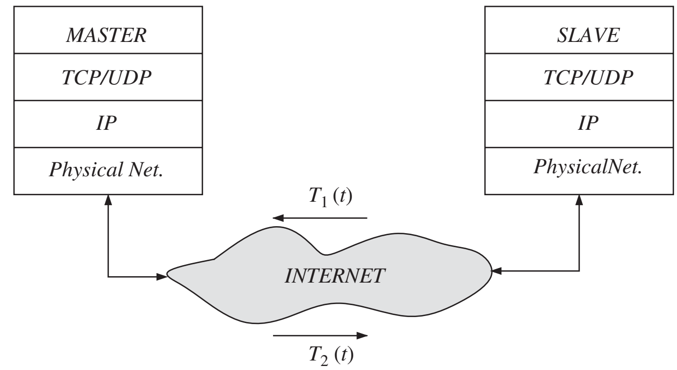

Fig. 6. Teleoperation over the Internet.

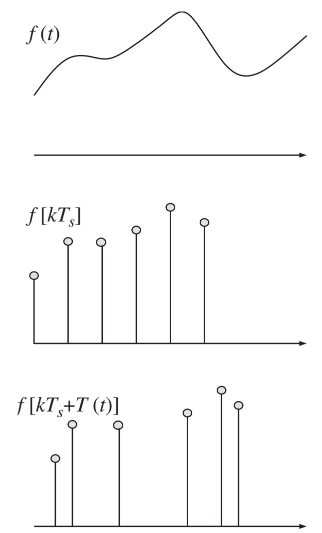

Fig. 7. Distortion of signals by time-varying delays in the channel.

As seen in Fig. 6, the master and slave have to transport their discrete-time information down the software layers until the physical layer after which the data packets undergo random time-varying delays $T_1(t)$ and $T_2(t)$, the forward and backward delays, respectively, which distort the transmitted signals as shown in Fig. 7. A choice between using transmission control protocol (TCP) or user datagram protocol (UDP) has to be made based on their performance; both residing at the transport layer in the ISO 7-layer reference model. On one hand, TCP provides reliable two-way communication and guarantees data delivery at the cost of retransmissions and long timeouts that are detrimental in real-time applications such as teleoperation. On the other hand, UDP does not require reception acknowledgments, at the expense of nonrecoverable data loss, eliminating unnecessary waiting time, which makes it appealing for realtime applications such as teleoperation (Oboe, 2001).

Results concerning fixed time delays had to be reexamined under the impact of the newly emerging communication medium, the Internet. For example, some earlier problems such

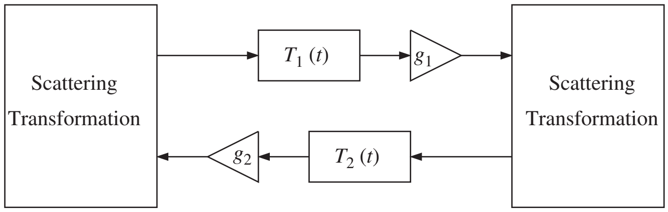

Fig. 8. Passivation of the channel.

as position drift between the master and slave that result from passivity-based control methods are aggravated by the time-varying delays. Moreover, performance is affected due to information losses and consequently reconstruction methods become necessary.

Naturally, having some knowledge of the delay behavior induced by communication over the Internet, or at least an upper bound on the delay value, is invaluable in designing adequate control laws. To this end some delay estimation schemes have been proposed, such as, using an autoregressive model as in Mirfakhrai and Payandeh (2002) or using some linear or nonlinear time series analysis as in Ye, Meng, Liu, and Li (2002).

3.7.1. Passivity under time-varying delays

As seen in Fig. 7, time-varying delays distort the signals being transmitted across the channel. Specifically, this distortion of the scattered/wave signals may introduce extra energy in the communication block. Therefore, a natural approach to tackle this problem is to dissipate the excess energy Lozano et al. (2002), as seen in Fig. 8. Let us look again at the energy calculation in (10)

$$E(t)=\frac{1}{2}\left\{\int_{t-T_1(t)}^{t} u_m^{\mathrm T}(\eta)u_m(\eta)\,\mathrm d\eta+\int_{t-T_2(t)}^{t} u_s^{\mathrm T}(\eta)u_s(\eta)\,\mathrm d\eta\right.$$
$$+\int_0^{t-T_1(t)} u_m^{\mathrm T}(\eta)u_m(\eta)\,\mathrm d\eta+\int_0^{t-T_2(t)} u_s^{\mathrm T}(\eta)u_s(\eta)\,\mathrm d\eta$$
$$-\int_0^{t} u_m^{\mathrm T}(\eta-T_1(\eta))u_m(\eta-T_1(\eta))\,\mathrm d\eta$$
$$\left.-\int_0^{t} u_s^{\mathrm T}(\eta-T_2(\eta))u_s(\eta-T_2(\eta))\,\mathrm d\eta\right\}.$$

By scaling the wave variables as

$$v_s(t)=g_1(t)u_m(t-T_1(t)),$$
$$v_m(t)=g_2(t)u_s(t-T_2(t))$$

and applying the change of variables formula $\sigma=\eta-T_i(t)$ for the independent time variable we obtain

$$E(t)=\frac{1}{2}\left\{\int_{t-T_1(t)}^{t} u_m^{\mathrm T}(\eta)u_m(\eta)\,\mathrm d\eta+\int_{t-T_2(t)}^{t} u_s^{\mathrm T}(\eta)u_s(\eta)\,\mathrm d\eta\right.$$
$$+\int_0^{t-T_1(t)}\left(\frac{1-T_1'-g_1^2}{1-T_1'}\right)u_m^{\mathrm T}(\sigma)u_m(\sigma)\,\mathrm d\sigma$$
$$\left.+\int_0^{t-T_2(t)}\left(\frac{1-T_2'-g_2^2}{1-T_2'}\right)u_s^{\mathrm T}(\sigma)u_s(\sigma)\,\mathrm d\sigma\right\}$$

from which we can extract the following sufficient condition that regains the passivity in the channel[2]

$$g_i^2=1-T_i'\geqslant 0,\quad i=1,2 \tag{13}$$

with the assumption that $T_i'\doteq \mathrm dT_i(t)/\mathrm dt$ are known for $i=1,2$ or at least an upper bound is available.

The above result can also accommodate for the presence of filters inside the wave domain and not just pure time-varying delays (Niculescu, Abdallah, & Hokayem, 2003). Assuming that the filters have $\mathscr{L}_2$ kernels given by h_1 and h_2, and T_1, T_2 are known upper bounds on the delay values, then we can rewrite the condition (13) as

$$g_i^2<\frac{1}{T_i\sup_{t>0}\int_{-T_i}^{0} h_i(t,\eta)^{\mathrm T}h_i(t,\eta)\,\mathrm d\eta},\quad i=1,2.$$

A straightforward way to regain passivity under time-varying delays are circumvented through the use of extra buffers (Kosuge, Murayama, & Takeo, 1996). The samples are assumed to be delayed by a *virtual delay* which is defined as a maximum bound on the possible delays, 95% of the time delay values which can be obtained experimentally. By introducing this virtual delay the original passivity argument for constant delays in Section 3.4 could be utilized again.

3.7.2. Position drift

General wave or scattering variables encode information about velocities and forces on both sides of the teleoperation channel; however, no explicit information about position is available which may result in position mismatch between the master and slave systems due to initial transient response or numerical roundoff errors. Furthermore, the delays being of time-varying nature aggravate the problem by contracting or stretching the wave signals in time, hence velocity information is distorted which in turn results in further position mismatch. This problem was addressed in Niemeyer and Slotine (1997a,b) and more recently in Chopra, Spong, Ortega, and Barabanov (2006) for the constant delay case, and Chopra, Spong, Hirche, and Buss (2003), Niemeyer and Slotine (1998) for variable delays.

3.7.2.1. Under constant delays A method for the constant delay case was presented in Niemeyer and Slotine (1997b), by transmitting a combination of the wave signal and its integral, then separating the two quantities at the receiver's side as shown in Fig. 9. Basically, this incorporates passive filtering in the wave domain that is known to preserve passivity. The new transmitted variable is

$$\overline{U}_*(t)=\int_0^t u_*(\tau)\,\mathrm d\tau+\frac{1}{\lambda}u_*(t)$$

and the received variable is $\overline{V}_*(t)=\overline{U}_*(t-T)$. On the receiver's side, $v_*(t)=\lambda(\overline{V}_*(t)-V_*(t))$, where $\overline{U}_*(t)=\int_0^t u_*(\tau)\,\mathrm d\tau$. This recovers the original wave signal and its integral both delayed

[2] In fact exact cancelation is not necessary, $g_i^2\leqslant 1-T_i'$ is sufficient.

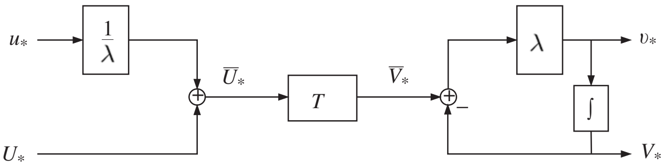

Fig. 9. Position drift compensation method proposed in Niemeyer and Slotine (1997b).

T seconds, from which we can extract the desired position directly as

$$x_{sd} = \frac{\sqrt{2b}V_s - p_s}{b},$$

where $p_s \doteq \int_0^t f_s(\eta)\,\mathrm{d}\eta$, the momentum of the control torque at the slave's side. Note that this is completely symmetric in the sense that if the master is also put under position control, the same procedure applies.

In Chopra et al. (2006), a new control architecture was proposed, in which the scattering transformation is used to encode velocities and forces, in addition to the position being explicitly sent across the communication channel both from master to slave and viceversa, where it is used in a proportional-type control. Accordingly, the control law in (6) becomes (for $T = T_1 = T_2$)

$$\begin{aligned} f_m(t) &= f_b(t) - f_{md}(t), \\ f_s(t) &= b_{s1}(\dot{x}_{sd}(t) - \dot{x}_s(t)) + f_f(t), \\ f_f(t) &= k(x_m(t-T) - x_s(t)), \\ f_b(t) &= k(x_s(t-T) - x_m(t)), \end{aligned} \tag{14}$$

under which the position tracking error signal

$$e(t) = x_m(t-T) - x_s(t) \tag{15}$$

is bounded under as long as $k < \sqrt{B_m B_s}/T$, and the velocities converge to zero. Moreover, under free-space condition ($f_e = 0$) the tracking error (15) goes to zero in steady state.

3.7.2.2. Under time-varying delays A solution to the drift problem in the variable delay case was proposed in Niemeyer and Slotine (1998), as variable delay would cause the loss of passivity besides the mismatch in position, as mentioned before. The proposed approach consists of transmitting $\int u(\tau)\,\mathrm{d}\tau$, which contains position information as seen earlier, along with $\int u^2(\tau)\,\mathrm{d}\tau$, which encodes the energy content present in the wave signal (note that both signals are delayed by $T(t)$). This last extra term can be used in monitoring the energy content of the utilized wave signal at the receiver's side. The wave is reconstructed on the receiver's side of the channel while observing the following two conditions:

(a) $\int_0^t v(\tau)\,\mathrm{d}\tau \to \int_0^{t-T(t)} u(\tau)\,\mathrm{d}\tau$, which ensures tracking and
(b) $\int_0^t v^2(\tau)\,\mathrm{d}\tau \leqslant \int_0^{t-T(t)} u^2(\tau)\,\mathrm{d}\tau$ that regains passivity condition.

In Chopra et al. (2003) the varying delay ($T_i(t)$, $i = 1, 2$) is addressed under a similar architecture as in (14) where $f_b = 0$, $f_f = k\,\mathrm{sat}_p(e)$, f_s is the coordinating torque defined in (6), and the saturation function is defined as

$$\mathrm{sat}_p(e) = \begin{cases} e & |e| \leqslant p, \\ p\,\frac{e}{|e|} & |e| > p. \end{cases}$$

Because of the time varying delay, only boundedness was obtained for the state vector $[\dot{x}_m(t), \dot{x}_s(t), x_{sd}(t) - x_s(t)]$.

Time-stamping was utilized in Yokokohji, Imaida, and Yoshikawa (1999) and Yokokohji et al. (2000) for sampled-data bilateral teleoperation in order to adjust the received samples in time and regain a perfect time-delay case. This also allows compensation for position drifts by incorporating compensators at the receivers' side in wave-variables domain as follows:

$$\begin{aligned} v_s(t) &= \tilde{v}_s(t) + K_s\left(\int_0^t v_s'(\eta)\,\mathrm{d}\eta - \int_0^{T_s^{\mathrm{limit}}(t)} v_s(\eta)\right), \\ v_m(t) &= \tilde{v}_m(t) + K_m\left(\int_0^t v_m'(\eta)\,\mathrm{d}\eta - \int_0^{T_m^{\mathrm{limit}}(t)} v_m(\eta)\right), \end{aligned} \tag{16}$$

where $\tilde{v}_s$ and $\tilde{v}_m$ are the received signals after passing through time-varying delays, and v_s' and v_s' are the time-adjusted samples, and

$$T_{s,m}^{\mathrm{limit}}(t) = \begin{cases} t & \text{if } t \leqslant t_{m,s}^{\mathrm{last}}(t) + \bar{T}_{1,2}, \\ t_{m,s}^{\mathrm{last}}(t) + \bar{T}_{1,2} & \text{otherwise} \end{cases}$$

and $\bar{T}_1$, $\bar{T}_2$ are average time delays. This integration compromises passivity of the channel, hence an energy monitoring scheme is proposed in Yokokohji et al. (2000) to augment the above compensation scheme, where the compensation equations (16) are enforced as long as the energy of the reconstructed wave signals is lower bounded by some pre-specified constants at the master and slave sides.

3.7.3. Continuous to discrete-time

As pointed out in Stramigioli, Secchi, van der Schaft, and Fantuzzi (2002) the interconnection of discrete-time and continuous-time systems is not necessarily passive when the continuous signals are merely sampled at the interconnection port and discrete-time signals are held for the duration of the sampling period h. Let us assume that the master and slave are controlled via a discrete-time control law Secchi, Stramigioli, and Fantuzzi (2003a,b) with the continuous-time system having admittance causality (which implies impedance causality for the controllers). Thus, we will have that the control force is held constant for the duration of the period

$$f(t) = f(k), \quad \forall t \in [kT, (k+1)T]$$

and accordingly we define the discrete-time velocity as

$$\dot{x}(k) = \frac{x((k+1)T) - x(kT)}{T} \doteq \left(\frac{\int_{nh}^{(n+1)h} \dot{x}(\eta)\,\mathrm{d}\eta}{T}\right) \tag{17}$$

in order to obtain the following equality in the energy flow

$$E(N) = h\sum_{k=0}^{N-1} f^{\mathrm{T}}(k)\dot{x}(k) = \int_0^{NT} f^{\mathrm{T}}(\eta)\dot{x}(\eta)\,\mathrm{d}\eta = E_c(NT)$$

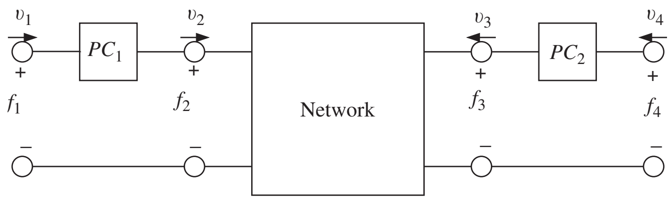

Fig. 10. Passivity controller.

which guarantees lossless connection between the two systems independent of the sampling period. With this discrete-time framework in mind, the scattering theory can be reformulated also in discrete-time (Secchi et al., 2003b), and passivity is guaranteed for fixed time delays as seen next.

3.7.4. Discrete-time scattering

The discrete-time scattering approach was presented in Kosuge and Murayama (1997) that parallels the development in Section 3.4. The discrete-time passivity condition for an n-port network is expressed as

$$\sum_{k=0}^{N} P(k) = \sum_{k=0}^{N} f(k)^{\mathrm{T}} \dot{x}(k) \quad \forall N \in \mathbb{N}$$

and the scattering matrix is expressed as $S(z)$, with respect to the discrete-shift operator. The scattered wave signals operating under constant time delay channel are then given by

$$\begin{aligned} u_m(k) &= f_{md}(k) + z_0 \dot{x}_m(k), \\ u_s(k) &= f_s(k) - z_0 \dot{x}_{sd}(k), \\ v_m(k) &= u_s(k-n), \\ v_s(k) &= u_m(k-m), \end{aligned}$$

where the signals are comparable to those given in Fig. 4, and n and m are the delays in forward and backward channel, respectively, which might be unequal. The corresponding scattering matrix is given by

$$S(z) = \begin{pmatrix} z^{-m} & 0 \\ 0 & z^{-n} \end{pmatrix} \quad \Rightarrow \quad \|S(z)\| = 1$$

and hence is passive.

3.7.5. Time-domain passivity

A recent approach to maintain passivity of the teleoperator has appeared in Ryu, Kwon, and Hannaford (2004, 2002) where discrete-time *passivity observer* (PO) and *passivity controller* (PC) were used to damp excess energy for bilateral controller comprised of controllers on both master and slave and the communication block (Fig. 10). The PO measures the energy level at both ports as

$$\frac{E_{\mathrm{obs}}(n)}{\Delta T} = W(n) = \sum_{i=0}^{n-1} (f_1(i)\dot{x}_1(i) + f_4(i)\dot{x}_4(i)) + f_2(n)\dot{x}_2(n) + f_3(n)\dot{x}_3(n), \tag{18}$$

where ΔT is the sampling time which is assumed faster than the dynamics of the system that permits this discrete-time representation. Hence, if $W(n) \geqslant 0$ the two-port network is passive, while if $W(n) < 0$ then there is an instance of energy extraction from either port and three main cases arise:

- $f_2(n)\dot{x}_2(n) < 0$ and $f_3(n)\dot{x}_3(n) \geqslant 0$, then energy is being extracted from port 2 and PC_1 is activated to dissipate the extra energy,
- $f_3(n)\dot{x}_3(n) < 0$ and $f_2(n)\dot{x}_2(n) \geqslant 0$, then energy is being extracted from port 2 and PC_2 is activated to dissipate the extra energy,
- $f_2(n)\dot{x}_2(n) < 0$ and $f_3(n)\dot{x}_3(n) < 0$ then energy should be dissipated at both ports and hence both PC_1 and PC_2 are activated.

The advantage of this passivity approach lies in the fact that it is model-insensitive, i.e. it can accommodate a large class of systems since its performance depends on measurements. Several issues that describe series or parallel implementation of the PC depending on impedance/admittance causality of the port can also be found in Ryu et al. (2004, 2002).

3.7.6. Quantization

Quantization imposes another constraint that may jeopardize passivity of system due to possible excess energy produced by quantization noise if left undamped (Secchi et al., 2003a). Assume we have a bounded quantization noise $d(t)$, with $\|d(t)\| \leqslant \Delta$, $\forall t$. The position signal is measured as

$$x_q(k) = x(k) + d(k),$$

where $(.)_q$ is the quantized value of the signal, and $x(k)$ is defined in the sense of Section 3.7.3. The discrete-time flow is given according to (17) as

$$\begin{aligned} \dot{x}_q(k) &= \frac{x(k+1) - x(k)}{T} = \dot{x}(k) + \frac{d(k+1) - d(k)}{T} \\ &= \dot{x}(k) + \delta(k), \end{aligned}$$

where $\|\delta(k)\| \leqslant 2\Delta/T$. Then, the excess energy that can be produced due to the quantization of signals can be upper bounded , by comparing the continuous-time and discrete-time energy levels during each sampling period, as

$$E_{\mathrm{excess}}(k) = f^{\mathrm{T}}(k)\delta(k)T \leqslant 2\Delta\|f^{\mathrm{T}}(k)\|.$$

Hence, passivity in the quantization process is guaranteed by dissipating an energy equal to $2\Delta\|f_q^{\mathrm{T}}(k)\|$ for each time step k. Naturally, this is a very conservative approach to deal with quantization and improvements are discussed in Secchi et al. (2003a).

3.7.7. Information loss

Packet loss is an inherent problem with packet-switched networks due to several factors such as transmission time-outs, transmission errors and limited buffer size. There are several strategies to deal with information losses within the passivity paradigm. Let us first analyze the impact on passivity of two common scenarios that deal with packet losses, namely using a *null packet* or *last packet*.

Consider a channel comprised of pure discrete delay elements where the wave signals are delayed by integer multiples of the sampling period

$$v_s(k) = u_m(k-m) \quad \text{and} \quad v_m(k) = u_s(k-n)$$

and m and n are integer multiples of the sampling period.

Null packet: A discrete-time calculation similar to that in (11) shows that using a null packet if no sample is received at time kh, where h is the sampling period, retains passivity in the case of constant delay (shown below) or time-varying delay:

$$E(k) = \frac{T}{2}\sum_{i=k-n+1}^{k}(\|u_m(i)\|^2 + \|u_s(i)\|^2) + \frac{T}{2}\sum_{i=1}^{k-n}(\|v_s(i)\|^2\beta_m(i) + \|v_m(i)\|^2\beta_s(i)) \geqslant 0,$$

where β_m and β_s indicate packet reception (=0) or loss (=1). Therefore, the energy content inside the channel is always lower bounded, indicating passivity. This is actually quite expected since using a null packet does not generate any extra energy.

Last packet: In this case nothing can be deduced about the passivity of the communication block since the use of previous signal value might involve utilizing more energy than the otherwise received signal value. This can be seen via the same kind of analysis as in the previous case

$$E(k) = \frac{T}{2}\sum_{i=k-n+1}^{k}(\|u_m(i)\|^2 + \|u_s(i)\|^2) + \frac{T}{2}\sum_{i=1}^{k-n}((\|v_s(i)\|^2 - \|v_s(i-1)\|^2)\beta_m(i) \times (\|v_m(i)\|^2 - \|v_m(i)\|^2)\beta_s(i))$$

which could possibly be unbounded from below, hence indicating loss of passivity.

Therefore, we need a scheme that lies in between the above two methods which can guarantee passivity of the channel and at the same time does not degrade the tracking performance substantially, as is the case with using a null packet. To this end, there are schemes that deal with such losses either passively interpolating lost samples as in Secchi et al. (2003a) and Berestesky et al. (2004) or using a model-based design as in Mastellone, Lee, and Spong (2006).

Passive interpolation: A passive linear interpolation scheme is used in Secchi et al. (2003a) to deal with packet losses. Assuming prior knowledge on the number of consecutively lost packets, say n, we can delay further (buffer) the transmission of the wave signals $n+1$ time steps and transmit with each wave sample the energy E_s of the n future samples in the buffer. This energy is used at the receiver's side to interpolate lost samples in a passive way. Since E_s represents energy content of n samples then each of the samples can contain an average energy given by

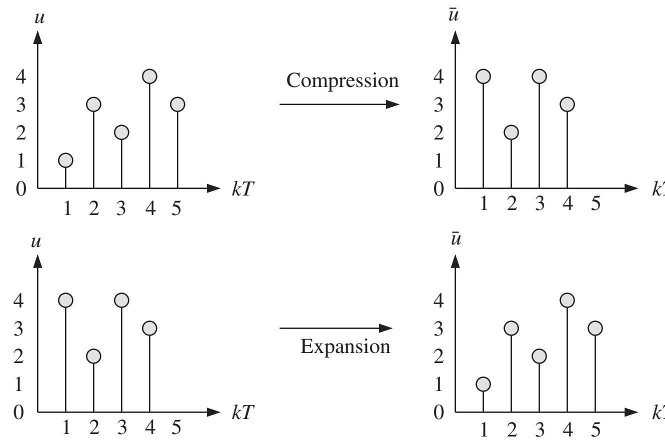

Fig. 11. Expanding and compressing the first and second samples.

$$\varepsilon = \frac{E_s}{n}.$$

Accordingly, if a packet is lost the following passive reconstruction condition is applied at the receiver's side

$$\hat{v}_I(i) = \alpha v_I(i), \quad i \in [k-n-1, k-1],$$
$$\alpha = \begin{cases} \sqrt{\dfrac{2\varepsilon}{T\|v_I(i)\|^2}}, & \dfrac{T}{2}\|v_I(i)\|^2 > \varepsilon, \\ 1 & \text{else.} \end{cases}$$

This is closely related to the positional drift method in Fig. 9, where a 'short-sighted' discrete-time integrator is implemented.

In Berestesky et al. (2004) the discrete-time counterpart of the position drift scheme shown in Fig. 9 is utilized when transmitting wave variable across a UDP-based packet switched network. This avoids the extra delay needed in Secchi et al. (2003a) to calculate the energetic content of the wave signals being transmitted by looking backward rather than forward. Moreover, Berestesky et al. (2004) introduces a signal management scheme (Fig. 11) that avoids data starvation or bursts at the receiver's end due to packet losses and/or delays. This is achieved via a *compressor* that merges the values of n received signal packets into one sample value according to the following formula:

$$\bar{v}_* = \operatorname{sgn}\left(\sum_{i=1}^{n} v_*(i)\right)\sqrt{\sum_{i=1}^{n} v_*^2(i)},$$

where $* = m, s$ as before, and an *expander* that decompresses the energy content of a single sample into n samples as follows

$$\bar{v}_*(i) = \operatorname{sgn}(v_*)\sqrt{\frac{v_*^2}{n}}, \quad i = 1, \ldots, n. \tag{19}$$

These two operations can be applied safely to the system and can achieve better performance, since the expander avoids abrupt changes in the command signal, which results from applying zero values whenever a packet is not received, and the compressor avoids discarding packets due to bursts in reception.

Model-based control: The work in Mastellone et al. (2006) adopts a different approach that employs approximate models to compensate for the lost samples in the communication network for the delay-free case. The network is modeled as two binary sequences that indicate packet losses in the forward and backward channels, respectively. Accordingly, the closed-loop system is hybrid in nature and passivity for such systems can be proven by considering all possible behaviors of the network and providing a common storage function that guarantees passivity under arbitrary switching in the network.

3.8. Passive decomposition

Passive decomposition Lee and Li (2001, 2002a,b, 2003a,b, 2003c); Li (1998) is a recent development that achieves passivity of the master and slave, through splitting the closed-loop teleoperator system into two subsystems; the *shape* and *locked* systems. The shape system (subindex E) maintains coordination between the master and slave, while the locked system (subindex L) determines the behavior of the overall motion of the master and slave.

Consider the system (*NL*) scaled by the following matrix $[\begin{smallmatrix}\rho I & 0\\ 0 & I\end{smallmatrix}]$, where $\rho > 0$ is a power scaling factor that affects the relative weighting of the human and environment input power to the teleoperator, given by

$$s_\rho(\dot{x}_m, \dot{x}_s, f_\mathrm{h}, f_\mathrm{e}) = \rho f_\mathrm{h}^\mathrm{T}\dot{x}_m + f_\mathrm{e}^\mathrm{T}\dot{x}_s \tag{20}$$

then the teleoperator is *energetically passive* if the energy is lower bounded as

$$\int_0^t s_\rho(\dot{x}_m, \dot{x}_s, f_\mathrm{h}, f_e)\,\mathrm{d}\eta \geqslant -c^2, \quad \forall t \in \mathbb{R}_+. \tag{21}$$

Hence, the objective of the control design is to ensure that (21) is satisfied for the closed-loop system between the human operator and the environment. This allows safe and stable interaction with passive human and environment.

Define the following nonlinear decomposition, with $x \doteq (x_m^\mathrm{T}\, x_s^\mathrm{T})^\mathrm{T}$:

$$\begin{pmatrix}\dot{x}_L\\ \dot{x}_E\end{pmatrix} = \underbrace{\begin{pmatrix} I-\phi(x) & \phi(x)\\ I & -I\end{pmatrix}}_{D(x)}\begin{pmatrix}\dot{x}_m\\ \dot{x}_s\end{pmatrix},$$

where $\phi(x) := (\rho M_s^{-1}(x_s)M_m(x_m) + I)^{-1}$, and $D(x)$ is nonsingular. Using this definition of $D(x)$ and pre-multiplying (*NL*) by $D^{-\mathrm{T}}(x)$ on the left we obtain the following two subsystems

$$M_L(x_L)\ddot{x}_L + C_L(x,\dot{x})\dot{x}_L + C_{LE}(x,\dot{x})\dot{x}_E = \tau_L + f_L,$$
$$M_E(x_E)\ddot{x}_E + C_E(x,\dot{x})\dot{x}_E + C_{EL}(x,\dot{x})\dot{x}_L = \tau_E + f_E$$

in which the (SS) property is preserved for the new inertia and Coriolis matrices of the transformed subsystems. Moreover, the coupling terms satisfy the following equality $C_{LE}(x,\dot{x}) + C_{EL}^\mathrm{T}(x,\dot{x}) = 0$. Also, the total energy of the original system (*NL*) also decomposes into the sum of the energies of the locked and shape systems, and we have the following proposition.

Proposition 6. *If the locked and shape systems are controlled using τ_L and τ_E to render the combined system passive, i.e.*

$$\int_0^t f_L^\mathrm{T}\dot{x}_L + f_E^\mathrm{T}\dot{x}_E\,\mathrm{d}\eta \geqslant -c_d^2, \quad \forall t \in \mathbb{R}_+ \tag{22}$$

then the original teleoperator is passive with respect to the supply rate (20).

Thus, the advantage of such method lies within the fact that it is easier to design control laws for the decoupled subsystems; the first controlling the gross motion of the teleoperator as it appears to the human through the locked system, and the second that controls the coordination of the master and slave motion and guarantees that $x_E \doteq x_m - x_s$ converges to zero. Such control law can be found in Lee and Li (2002a,b, 2005) that consists of cancelation of the cross coupling terms $C_{LE}(x,\dot{x})$ and $C_{EL}(x,\dot{x})$, feedback PD control, motion guidance/obstacle avoidance and passive compensation of the external force f_E and the apparent inertia scaling through utilizing the idea of fictitious energy reservoir with flywheel dynamics. Stability with large delays in force sensing was also experimentally shown in Lee and Li (2003c, 2005) and an extension to n-systems was proposed in Lee and Li (2003a).

This passive decomposition method has been recently coupled with the scattering transformation to teleoperate multiple slave robots through a delayed communication channel in Lee, Martinez-Palafox, and Spong (2005), Lee and Spong (2005a).

3.9. Adaptive control

In Chopra, Spong, and Lozano (2004) an adaptive scheme is considered that deals with parametric uncertainty, where a new mixed position-velocity signal is transmitted in the wave equations (9) instead of just velocity. Consider the system (*NL*) and define the following signals:

$$r_m := \dot{q}_m + \lambda q_m,$$
$$r_s := \dot{q}_s + \lambda q_s$$

for the master and slave, respectively. Then, using the fact that (*NL*) is linearly parameterizable (Spong et al., 2005), and using the feedback law

$$f_m = -f_{md} - \hat{M}_m(q_m)\lambda\dot{q}_m - \hat{C}_m(q_m,\dot{q}_m)\lambda q_m,$$
$$:= -f_{md} - Y_m\hat{\theta}_m,$$

$$f_s = f_{sd} - \hat{M}_s(q_s)\lambda\dot{q}_s - \hat{C}_s(q_s,\dot{q}_s)\lambda q_s$$
$$:= f_{sd} - Y_s\hat{\theta}_s$$

results in the following closed-loop system

$$M_m\dot{r}_m + C_m r_m = Y_m\tilde{\theta}_m + f_\mathrm{h} - f_{md},$$
$$M_s\dot{r}_s + C_s r_s = Y_s\tilde{\theta}_s + f_{sd} - f_\mathrm{e},$$

where $\tilde{\theta}_m \doteq \theta_m - \hat{\theta}_m$, $\tilde{\theta}_s \doteq \theta_s - \hat{\theta}_s$ are the estimation errors. The update laws for the parameters ($\dot{\hat{\theta}}$ and $\hat{\theta}$) can be deduced from a Lyapunov-like argument. Using this scheme, it can be shown that the parameter estimation errors remain bounded, and that the errors defined between the master and slave positions converge to zero asymptotically.

3.10. Passivity without the scattering variables

Recently, two approaches have appeared that do not rely on the scattering formulation to provide passivity of the teleoperator. The first method is based on the adaptive control laws in Section 3.9 and views the master and slave as two systems that are output passive and are synchronizing their positions across the network (Chopra & Spong, 2005). This approach does not use any wave-like encoding scheme, instead the input forces are computed directly as

$$f_{md} = K(r_s(t-T) - r_m(t)),$$
$$f_{sd} = K(r_m(t-T) - r_s(t)),$$

where $K > 0$ and r_* are defined as before. With these control laws we can guarantee exponential convergence to the origin of the error signals given by

$$e_m(t) = x_m(t-T) - x_s(t),$$
$$e_s(t) = x_s(t-T) - x_m(t).$$

The second method uses a PD-type control law (Lee & Spong, 2006a, 2005b, 2006b) given by

$$\begin{aligned} f_m(t) = & -K_d\dot{x}_m(t) - K_p\,(x_m(t) - x_s(t-T_2)) \\ & - K_v(\dot{x}_m(t) - \dot{x}_s(t-T_2)), \end{aligned}$$

$$\begin{aligned} f_s(t) = & -K_d\dot{x}_s(t) - K_p\,(x_s(t) - x_m(t-T_1)) \\ & - K_v(\dot{x}_s(t) - \dot{x}_m(t-T_1)) \end{aligned}$$

which, when coupled with some frequency domain condition on K_d, can provide passivity of the overall closed-loop system, and ideal force reflection in steady state ($f_{\mathrm{h}} \to -f_{\mathrm{e}}$).

4. Additional control techniques

4.1. Transparency and the 4-channel architecture

Transparency is one of the main objectives in teleoperation since it provides the human with a *feeling* of the remote environment. This essential objective in teleoperation can be realized whenever the input (or transmitted) impedance seen by the human operator mimics the impedance of the remote environment, i.e. (see Fig. 12)

$$Z_t = Z_{\mathrm{e}}. \tag{23}$$

In the early 1990s, it was realized independently in Lawrence (1992) and Yokokohji and Yoshikawa (1994) that, in order to achieve transparency, velocity and force feedback should be utilized in designing control laws for both the master and slave. In other words, implementing a 4-*channel architecture* through transmitting $\dot{x}_m$ and f_m in one direction and $\dot{x}_s$ and f_s in the other direction is required to realize the equality in (23).

The use of 2-port network theory surfaced again in this framework, since the master–slave system (without the environment

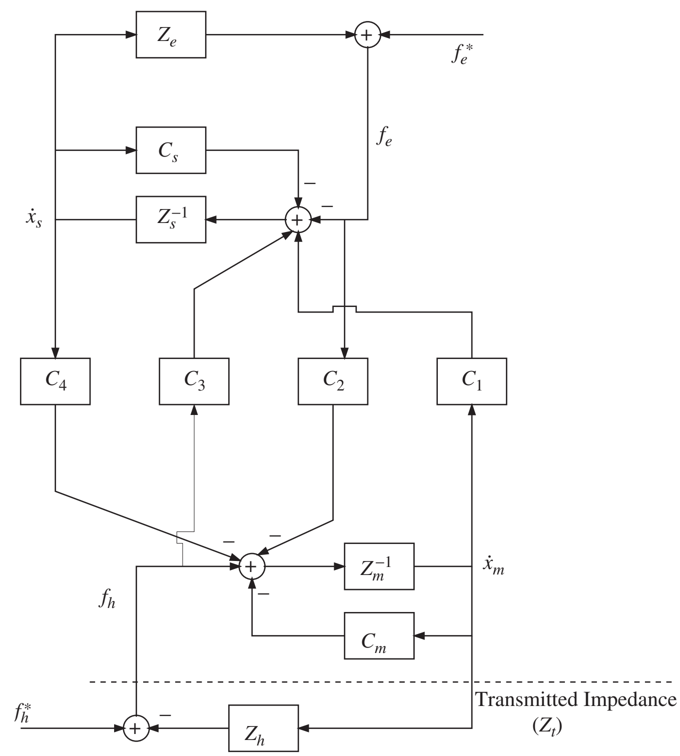

Fig. 12. 4-Channel architecture.

and human operator) can be represented through the hybrid matrix Lawrence (1992) (or equivalently chained matrix Yokokohji & Yoshikawa, 1994) given by

$$\begin{pmatrix} f_{\mathrm{h}}(s) \\ \dot{x}_m(s) \end{pmatrix} = \underbrace{\begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix}}_{H(s)} \begin{pmatrix} \dot{x}_{\mathrm{e}}(s) \\ -f_{\mathrm{e}}(s) \end{pmatrix} \tag{24}$$

which gives

$$Z_t = (h_{11}(s) - h_{12}(s)Z_{\mathrm{e}})(h_{21}(s) - h_{22}(s)Z_{\mathrm{e}})^{-1}. \tag{25}$$

Thus, depending on h_{ij} in (24), we can conclude the level of transparency of the teleoperator as compared to the ideal response

$$H_{\mathrm{ideal}} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

Note that the approaches in Lawrence (1992) and Yokokohji and Yoshikawa (1994) are identical and realize transparency through canceling the dynamics of the master and slave. Furthermore, requiring the two-way communication of both forces and velocities subsumes the bilateral teleoperation setting presented earlier.

As seen in Fig. 12, we have four control blocks in the channel that are utilized to vary the elements of the hybrid matrix H in order to achieve transparency. The communication channel is designed based on the controlled dynamics of the master and slave as following: let Z_m, Z_s, C_m, and C_s be the master impedance, slave impedance, master controller and slave controller, respectively. Also consider transmitting the operator's input force F_h via C_3, the environment force F_e via C_2, the master's velocity $\dot{x}_h$ via C_1 and the slave's velocity $\dot{x}_e$ via C_4. Then the elements of H in (24) are given by

$$\begin{aligned}
h_{11} &= (Z_m + C_m)P(Z_s + C_s - C_3C_4) + C_4,\\
h_{12} &= -(Z_m + C_m)P(I - C_3C_2) - C_2,\\
h_{21} &= P(Z_s + C_s - C_3C_4),\\
h_{22} &= -P(I - C_3C_2),\\
P &= (C_1 + C_3Z_m + C_3C_m)^{-1} \qquad (26)
\end{aligned}$$

and the objective for transparency is to make Z_t mimic the impedance of the environment Z_e. From (26) we can see that this objective can be realized by setting

$$\begin{aligned}
&C_3C_2 = I, &&C_2 = I,\\
&C_4 = -(Z_m + C_m), &&C_1 = Z_s + C_s
\end{aligned}$$

or equivalently the control input torques are given by

$$\begin{aligned}
f_m &= [-C_m \;\; I]\begin{bmatrix}\dot{x}_m\\ f_h\end{bmatrix} - [C_4 \;\; C_2]\begin{bmatrix}\dot{x}_s\\ f_e\end{bmatrix},\\
f_s &= [C_1 \;\; C_3]\begin{bmatrix}\dot{x}_m\\ f_h\end{bmatrix} - [C_s \;\; I]\begin{bmatrix}\dot{x}_s\\ f_e\end{bmatrix}. \qquad (27)
\end{aligned}$$

However, to implement C_1 and C_4, acceleration measurements may be required and a method to circumvent this problems is to allow the transmitted impedance to be (Zhu & Salcudean, 1995)

$$Z_t = Z_m + Z_e \qquad (28)$$

which results from the following design of channel controllers

$$C_1 = C_s, \quad C_2 = C_3 = I, \quad C_4 = -C_m.$$

It was argued that the use of the four channels is necessary for achieving transparency, however it might be done at the expense of losing passivity and robustness to delays. While the 2-channel architectures viewed earlier in Section 3 guarantee passivity, they do so at the expense of losing transparency. Thus, it was concluded that "passivity and transparency are conflicting objectives in teleoperator system design" (Lawrence, 1992).

4.1.1. Scaling

Within the 4-channel context it is also possible to achieve scaling between the master and slave velocity and force (Zhu & Salcudean, 1995) where the hybrid matrix in (2) can be realized as

$$H(s) = \begin{pmatrix} Z_m(s) & G(s)\\ -\dfrac{1}{G(s)} & 0\end{pmatrix}$$

which realizes the adjusted transferred impedance in (28) and a scaling in velocity, and an experimental implementation of the above scheme appeared in Zhu, Salcudean, and Zhu (1999).

Improvements in the design techniques were suggested to the 4-channel approach in Hashtrudi-Zaad, Mobasser, and Salcudean (2003), Mobasser and Hashtrudi-Zaad (2004), Mobasser, Hashtrudi-Zaad, and Salcudean (2003), Salcudean, Hashtrudi-Zaad, Tafazoli, DiMaio, and Reboulet (1999), Salcudean, Hashtrudi-Zaad, Tafazoli, DiMaio, and Reboulet (1998), and others pertaining to adaptive control that we see in the next section.

4.1.2. Adaptation

In Section 4.1, we saw that a 4-channel architecture is necessary to achieve transparency between the environment and the human operator. However, it assumed perfect knowledge of the master, slave, environment and operator impedances in order to realize the fixed compensators. Hence, adaptive control has been employed as a tool to mitigate the effects of parameter uncertainty in the master and slave robots (Ryu & Kwon, 2001), uncertainty in the environment (Hashtrudi-Zaad & Salcudean, 1996) or both (Lee & Chung, 1998; Shi, Tao, Liu, & Hunter Downs, 1999; Zhu & Salcudean, 1999).

Within the 4-channel context in Section 4.1, Hashtrudi-Zaad and Salcudean (1996) proposes an adaptive scheme that achieves transparency without force feedback ($C_2 = C_3 = 0$). The controllers C_1 and C_s are designed based on the adaptive control law, while C_4 and C_m are designed to achieve transparency and are given by $C_4 + C_m = \hat{Z}_e - Z_m$. The adaptive law is derived by making use of the slave impedance $Z_s = m_s s + b_s$ and the environment impedance $Z_e = m_e s + b_e + d_e/s$. Then the resulting dynamics of the combined slave-environment system are given by

$$m_s\ddot{x}_s + b_s\dot{x}_s = f_s - f_e \qquad (29)$$

since $f_e = Z_e\dot{x}_s$, which can be written as

$$\begin{aligned}
f_s &= (m_s + m_e)\ddot{x}_s + (b_s + b_e)\dot{x}_s + k_e x_s\\
&= Y\theta, \qquad (30)
\end{aligned}$$

where Y is the regressor vector and θ is the parameter vector to be estimated. The composite adaptive scheme utilized is given by

$$f_s = \underbrace{[\ddot{x}_r\; \dot{x}_r\; x_s]}_{\bar{Y}}\,\hat{\theta} - k_v(\dot{x}_s - \dot{x}_r),$$

where $\dot{x}_r = \dot{x}_{md} - \lambda(x_s - x_{md})$ and $\lambda > 0$, that depends on the reference position, velocity and acceleration sent by the master. Several update laws for $\hat{\theta}$ were suggested, which reflect into the structure of C_1, C_s and C_m. A similar adaptation law was provided in Lee and Chung (1998) and the cases of jumping smoothly time-varying parameters were addressed in Shi et al. (1999).

A different approach was undertaken in Zhu and Salcudean (1999) that uses adaptation on both sides of the teleoperator, i.e. separate adaptive laws for the master and human operator on one side and slave with environment on the other side. It lifts the problem setting into the full nonlinear dynamical equations of motion and adds local force feedback on each side that achieve robustness against uncertainties in parameters and channel delays. Transparency however, is not in the sense (Lawrence, 1992) anymore, i.e. the human sees the scaled impedance of the environment plus a transparency error term that results from the teleoperator behaving as a mass-damper system. Another adaptive approach was presented in Ryu and Kwon (2001) which ignores the environment and human operator parameters in the adaptation law and concentrates on achieving similar closed-loop dynamics on both sides of the channel resulting in scaled position and force tracking along with ideal transparency.

4.2. Sliding-mode control

The application of sliding-mode control to 1-DOF delay-free teleoperated system (L) appeared in Buttolo, Braathen, and Hannaford (1994) and was later extended to time-varying delayed communication in Cho, Park, Kim, and Park (2001), Park and Cho (1999, 2000). The main idea is to consider a sliding surface comprised of the error between the positions and velocities of the master and slave, that is,

$$s = \dot{\tilde{x}} + \lambda\tilde{x},$$

where $\tilde{x} := x_s - k_x x_m$, and k_x is a position scaling factor. Standard methods to derive control laws that guarantee stability to the surface s are available in such case, however, they depend on estimates of the external human and environment forces, $\hat{f}_{\mathrm{h}}$ and $\hat{f}_{\mathrm{e}}$, respectively. Large gains are required in the case that the estimates are far from the actual forces to enforce the dissipation condition $s\dot{s} \leqslant -\eta\|s\| < 0$.

4.3. $\mathscr{H}_\infty$ design

$\mathscr{H}_\infty$ and μ-synthesis design procedures can be utilized to derive compensators for delayed teleoperators, that take into account worst case upper bound on the delay values in the forward (master-to-slave) and backward (slave-to-master) communication (Leung et al., 1995). Consider the linear system (L), from which the models for the master and slave can be written in the frequency domain as $P_m(s)$ and $P_s(s)$, respectively. A two-step design procedure can be performed in order to design compensators for the free motion case (using $\mathscr{H}_\infty$) and then for the delayed constrained motion (using μ-synthesis).

Free motion controllers: The controllers C_m and C_s for the master and slave, respectively, can be designed separately within the context of $\mathscr{H}_\infty$ as follows:

$$C_m: \quad z = \begin{bmatrix} W_{m1}(f_{\mathrm{h}} - \dot{x}_m) \\ W_{m2} f_{m1} \end{bmatrix}, \quad w = \begin{bmatrix} f_{\mathrm{h}} \\ d_{m1} \end{bmatrix},$$

$$y = \dot{x}_m + W_{m3} d_{m1}, \quad u = f_{m1},$$

$$C_s: \quad z = \begin{bmatrix} W_{s1}(\dot{x}_m - \dot{x}_s) \\ W_{s2} f_{s1} \end{bmatrix}, \quad w = \begin{bmatrix} f_{\mathrm{h}} \\ d_{s1} \\ d_{s2} \end{bmatrix}$$

$$y = \begin{bmatrix} \dot{x}_m + W_{s3} d_{s1} \\ \dot{x}_s + W_{s4} d_{s2} \end{bmatrix}, \quad u = f_{s1},$$

where in both cases z, w, y, u, d_* and W_* are the performance output, exogenous signals, measured outputs, control inputs, disturbances and weighting matrices, respectively.

Constrained motion controller: Having designed optimal controllers for the free motion, the delay can be considered as

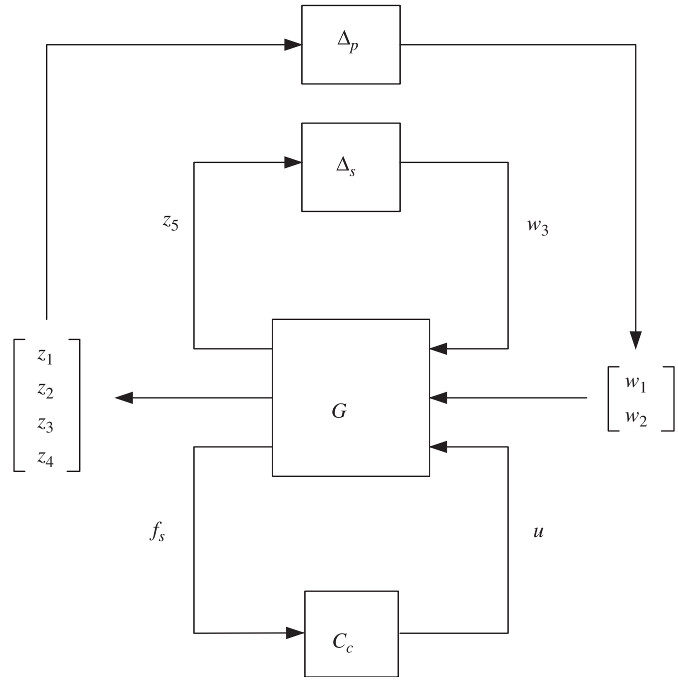

Fig. 13. μ-synthesis.

a perturbation to the constrained motion case, i.e. when the slave is in contact with the environment of known impedance Z_{e}, and the extra controller C_c can be utilized to account for both delays and constrained motion. The delays in the forward and backward channels can be combined into a single element T which appears as perturbation to the system of the form

$$\Delta_T(s) = \mathrm{e}^{-sT} - 1$$

such that $\|\Delta_T(\mathrm{j}\omega)\|_\infty = 2$. This perturbation can be filtered to render its norm < 1, and the μ-synthesis design procedure can be applied to the system shown in Fig. 13, to design C_s, where

$$C_c: \quad z = \begin{bmatrix} W_1(\dot{x}_m - \dot{x}_s) \\ W_2(f_s - (\tau_{m1} + f_{m2})) \\ W_3 f_{m2} \\ W_4 f_{s2} \\ z_5 \end{bmatrix}, \quad w = \begin{bmatrix} f_{\mathrm{h}} \\ f_b \\ w_3 \end{bmatrix},$$

$$y = f_s, \quad u = \begin{bmatrix} \tau_{m2} \\ \tau_{s2} \end{bmatrix}$$

and Δ_p is a fictitious performance perturbation.

The above method accounts for all possible delays within a range which is in many cases too conservative. Thus, the use of gain scheduling was suggested in Sano et al. (1998), which encompasses designing controllers for several values of the delay and applying them according to the current value of the delay encountered. The controller is then varied according to updated measurements of the delay which is greatly suitable for Internet-based teleoperation.

In Boukhnifer, Ferreira, and Fontaine (2004), scaling elements were introduced into the forward and backward loop and a similar μ-synthesis design procedure was performed in designing for stabilizing controller C_c, while taking into account stability under prespecified ranges of scaling parameters as an extra objective.

Other instances of $\mathscr{H}_\infty$ have appeared in Hu, Salcudean, and Loewen (1995) and Yan and Salcudean (1996), where the 4-channel formulation was utilized in order to design a controller similar to that in (27), with a modified problem to include minimizing the passivity distance as a performance criterion which is defined as

$$v := -\inf_{\omega\in\Re}\{\mathrm{Re}(G_{f_\mathrm{e}\to\dot{x}_s}(\mathrm{j}\omega))\},$$

where $G_{f_\mathrm{e}\to\dot{x}_s}$ is the transfer function, from the environment force f_e to the slave's velocity $\dot{x}_s$. Also, delay-free analysis dealing with modeling uncertainties can be found in Lee, Tanie, and Chung (1999), while preliminary analysis including constant delays using Smith predictor for free motion and $\mathscr{H}_\infty$ for constrained motion appeared in Lee and Jeong (1994).

4.4. *Frequency domain stability analysis*

The frequency domain approach can be applied for linear systems to describe delay-dependent and delay-independent asymptotic stability of the teleoperator (Eusebi & Melchiorri, 1998; Niculescu, Taoutaou, & Lozano, 2003; Taoutaou, Niculescu, & Gu, 2003). The teleoperator in Fig. 3 is viewed as a single system with transport delays in the forward and backward channels between the master and slave subsystems. These methods can be used as analysis tools, assuming the feedback structure is given, in order to derive ranges for the control gains that provide asymptotic stability. Thus, this method circumvents the use of passivity-based control as means to deduce stability.

In the case of commensurate delays the closed-loop equations of the (L) teleoperator can be written as (Eusebi & Melchiorri, 1998)

$$\dot{x}(t) = \sum_{k=0}^{p} A_k x(t-kT), \qquad T \geqslant 0, \tag{31}$$

where $x = [x_m^\mathrm{T}\ \dot{x}_m^\mathrm{T}\ x_s^\mathrm{T}\ \dot{x}_s^\mathrm{T}]^\mathrm{T}$ is the closed-loop state vector. Then the following theorem can be applied to deduce delay-dependent and delay-independent stability.

Theorem 7 (*Eusebi & Melchiorri, 1998*). *Define*

$$\Psi(\theta) = \det\left\{\left(\sum_{k=0}^{q} A_k \mathrm{e}^{-\mathrm{j}k\theta}\right)\otimes I_n + I_n \otimes \left(\sum_{k=0}^{q} A_k \mathrm{e}^{\mathrm{j}k\theta}\right)\right\},$$

where $\otimes$ is the Kronecker product. If $\Psi(\theta)\neq 0$, $\forall\theta\in[0,\pi]$, then (31) *is asymptotically stable independent-of-delay, otherwise* (31) *is asymptotically stable if*

$$T < \bar{T} = \begin{cases} \bar{\theta}/\omega_{\max}, & \omega_{\max}\neq 0 \\ \infty, & \omega_{\max} = 0, \end{cases}$$

where $\bar{\theta}$ is the least number in the interval $[0,\pi]$ such that $\Psi(\bar{\theta})=0$, and

$$\omega_{\max} = \max\left\{\frac{1}{2}\lambda_M(\mathrm{j}A_0^a),\ \max_{\theta\in[0,2\pi]} \times\left(\frac{1}{2}\left(\mathrm{j}A_0^a + \sum_{k=1}^{q}[\mathrm{j}A_k^a\cos(k\theta) - A_k^s\sin(k\theta)]\right)\right)\right\},$$

where $A_k^s = A_k + A_k^\mathrm{T}$ and $A_k^a = A_k^\mathrm{T} - A_k$.

Using the above setting it was shown that the wave formulation with impedance matched terminals (Section 3.5.1) is asymptotically stable independent of delay. The shared compliant control was also tested within this framework, and proved to possess delay-dependent asymptotic stability. A new scheme was proposed that modifies the shared compliant control by making the force reflection gain dynamic, which constitutes an extra degree of freedom that can be used to achieve better transparency while retaining stability.

A different approach is given in Niculescu et al. (2003) that aims at proving closed-loop stability of the delayed teleoperator system in Fig. 3, without utilizing the scattering transformation, by deriving conditions on the system parameters that guarantee stability of the transfer function from the input force of the operator f_h to the velocity of the slave $\dot{x}_s$. Consider the Laplace domain representation of system (L) with a PD control input given by

$$f_s(s) = \left(\frac{k_s}{s} + b_{s1}\right)\mathrm{e}^{-Ts}\dot{x}_m(s) - \dot{x}_s(s),$$
$$f_m(s) = -\mathrm{e}^{-Ts}\tau_s(s).$$

Then the transfer function from f_h to $\dot{x}_s$ is given by

$$G_{f_\mathrm{h}\dot{x}_s}(s) = \frac{1}{Z_3(1+\mathrm{e}^{-2Ts}Z_1Z_2/(Z_1+sZ_2)1/Z_3)}\,\frac{Z_1}{Z_1+sZ_2},$$

where

$$Z_1 = B_{s1}s + K_s,$$
$$Z_2 = M_s s + B_s + (1+\alpha_f)Z_\mathrm{e},$$
$$Z_3 = M_m s + B_m.$$

Using Tsypkin's criterion gives the following necessary and sufficient condition for stability independent of the delay value.

Theorem 8 (*Niculescu et al., 2003*). *Assume $b_m > b_s + (1+\alpha_f)z_\mathrm{e}$ then $G_{f_\mathrm{h}\dot{x}_s}(s)$ is asymptotically stable independent-of-delay iff*

$$|Z_3(\mathrm{j}\omega)| > \left|\frac{Z_1(\mathrm{j}\omega)Z_2(\mathrm{j}\omega)}{Z_1(\mathrm{j}\omega)+\mathrm{j}\omega Z_2(\mathrm{j}\omega)}\right|, \qquad \forall\omega>0. \tag{32}$$

However, assume that condition (32) is not satisfied for all frequency values then a delay dependent stability condition can be utilized based on the first frequency for which equality is achieved in (32).

Theorem 9 (Niculescu et al., 2003). *Assume $b_m > b_s + (1+\alpha_f)z_e$ then $G_{f_h\dot{x}_s}(s)$ is asymptotically stable for all delay values $T \in [0, T^*]$ where*

$$T^* = \min_i \frac{1}{2\omega_i} \arccos\left(-\frac{A(\omega_i)B_m + \omega_i B(\omega_i)M_m}{B_m^2 + \omega_i^2 M_m^2}\right),$$

ω_i's are the positive roots of the equation $A(\omega)^2 + B(\omega)^2 = B_m^2 + \omega^2 M_m^2$, and

$$A(\omega) = \Re e\left\{\frac{Z_1(j\omega)Z_2(j\omega)}{Z_1(j\omega) + j\omega Z_2(j\omega)}\right\},$$
$$B(\omega) = \Im m\left\{\frac{Z_1(j\omega)Z_2(j\omega)}{Z_1(j\omega) + j\omega Z_2(j\omega)}\right\}.$$

Theorems 8 and 9 can be utilized to derive sufficient conditions on the controller parameters b_{s1} and k_s that guarantee stability in both cases of delay-dependent and delay-independent stability. The same approach is followed in Taoutaou et al. (2003) for unequal delay values in the forward and backward channels. Also Taoutaou et al. (2003) gives some results when delays are slightly perturbed by an unknown and bounded functions with bounded derivatives, thus the delays become time-varying.

4.5. Model predictive control

All the previous control schemes have assumed unrestricted phase and input spaces over which the teleoperator evolves. Model predictive control (as in Bemporad, 1998; Sheng & Spong, 2004), on the other hand, can accommodate restrictions such as

$$\underline{f}_s \leqslant f_s \leqslant \overline{f}_s,$$
$$\underline{f}_m \leqslant f_m \leqslant \overline{f}_m$$

on the control inputs. Moreover, due to its predictive nature MPC naturally can handle delays of fixed or variable nature by extending the optimization horizon to encompass the largest possible value for the delay. Stability in such scheme is implicit rather than explicit, that is, it is either reflected in the cost criterion or constraints.

5. Applications

Bilateral teleoperation has been applied over the past 50 years in various contexts, ranging from operating space robots from ground, commanding unmanned underwater vehicles, handling hazardous materials, to manoeuvering mobile robots with obstacle avoidance. Many of the theoretical concepts reviewed throughout the previous sections have been utilized directly or indirectly to achieve stable, user-friendly, and transparent teleoperation.

5.1. Handling hazardous material

The earliest application of teleoperated manipulators was handling nuclear materials. The issues involved within such a task are exactly those we have discussed throughout this survey (Clement et al., 1985), such as motion scaling, visual feedback, workspace constraints, and force feedback. Also a recent application appeared in Wang and Yuan (2004) for detecting leaks of sealed radioactive materials.

5.2. Telesurgery

Teleoperation has found fertile grounds in medical applications such as telesurgery. Telesurgery permits the exchange of medical expertise around the world without requiring the physician to travel. This saves time, money and effort by bringing the remote surgery room to the fingertips of the surgeon. Design issues in telesurgery can be found in Funda et al. (1996), Madhani et al. (1998), Taylor et al. (1995), and recently remote telesurgery experiments have been reported between Italy and USA in Rovetta, Sala, Wen, and Togno (1996), where time delays are a major concern.

5.3. Underwater vehicles

During the 1970s and 1980s one of the main applications of teleoperation was in unmanned underwater vehicles for scientific exploration or military applications. The use of the tethers to control such vehicles is not practical as they get caught and tangled. On the other hand transmitting control and feedback signals through aquatic media introduces significant delays which affect the performance and even stability.

The concurrent method for dealing with teleoperated systems was the supervisory control, thus the time delay problem was tackled from this angle (Funda & Paul, 1991; Madni et al., 1983; Yoerger & Slotine, 1987; Yoerger et al., 1986). One of the earlier control of underwater manipulators appeared in Uhrich (1973) where force feedback was utilized.

5.4. Space robots

Space exploration and operation in geosynchronous orbits necessitates the use of teleoperated robots (Skaar & Ruoff, 1994) which reduces cost of assembly, maintenance and repair tasks in space and on the other hand reduces the risk in the astronauts' safety. Numerous publications have appeared in this area, such as Bejczy and Szakaly (1987), Hirzinger (1987), Hirzinger et al. (1993), Hirzinger et al. (1989), Imaida et al. (2004), Jenkins (1986), Lee et al. (1985), Yoon et al. (2004).

More recently, experiments were conducted (Imaida et al., 2004; Yoon et al., 2004) that allow teleoperation of a 6DOF robotic arm on board the Engineering Test Satellite 7 (ETS-VII) in orbit with over a 7 s delay, using the virtual environment scheme and predictive display.

Germany's ROKVISS is one of the more recent projects towards these objectives, which is aimed at conducting experiments in outer space of lightweight robotic manipulators (http://www.robotic.dlr.de/).

5.5. Mobile robots

Mobile robots have recently emerged as a new application of bilateral teleoperation (Diolaiti & Melchiorri, 2002; Hong et al., 1999; Kawabata et al., 1999; Lim et al., 2003; Makiishi & Noborio, 1999; Rösch et al., 2002; Schilling & Roth, 1999). Once operating in a remote location, mobile robots send visual feedback to the human operator that allows her/him to assess the surroundings and issue a corrective command. However, this requires a high bandwidth to transmit real-time visual data to the operator, besides the fact that the camera has a limited viewing angle. This necessitates the need to send an extra force feedback signal to the operator allowing him to sense the surrounding of the mobile robot and alleviating the need for high quality visual feedback. Although mobile robots do not fall into the traditional teleoperation setting, since kinematic similarity between the master and slave is eliminated, it is still possible to place them under force feedback through the use of a haptic device as Diolaiti and Melchiorri (2002) and more recently Lee, Martinez-Palafox, and Spong (2006) which also incorporates time delays into the communication loop.

6. Conclusions and future directions

The eventual return of humans to the moon as a first step towards colonization of Mars and beyond will require that robots and humans work closely together. For example, in order to construct a base station on the moon it is not feasible to send a large human construction crew, nor is it likely that fully autonomous robots would be capable of completing such a task in the near future. Teleoperation thus represents the most likely scenario for large scale construction projects in earth orbit or on the moon. Moreover, the scalability from one-to-one master–slave architecture to many-to-many architecture is yet to come over the next few decades and is the subject of extensive current research.

Telemedicine is an area that requires great care in teleoperation since mistakes are life threatening; moreover, delays and loss of information could be fatal. The basic results in this area we have presented in this paper can be further expanded along the lines of remote surgery and possibly remote examination (palpation, etc.). First responders at an accident scene, fire, or other disaster would benefit from having robotic devices that can communicate wirelessly, carry video, audio, and tactile sensors, and have manipulation capability to rescue, examine, or administer first aid to victims. Multiple such devices could be used within large buildings and would have to communicate among themselves and with a human operator.

In a mobile robotic context, the recent problem of coordinating multiple mobile *agents* to achieve a common heading or perform a certain task is a natural extension since the one-to-one teleoperation can be scaled into one-to-many setting. However, adopting centralized versus decentralized control for this problem is still a research topic.

These applications suggests that the next step in bilateral teleoperation is to take a leap from one-to-one master slave system onto one-to-many, as in Fig. 14, or even n-to-m master slave systems. Several questions arise in such a scenario pertaining to the control structure to be utilized; broadcasting desired task to all slaves or just communicating with one that acts as an information relay.

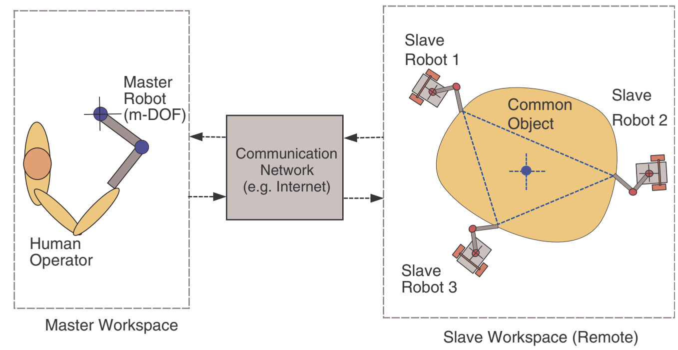

Fig. 14. Single master operator commanding multiple slaves.

Finally, in the area of nanotechnology, nanomanipulation and teleoperation offers many challenging problems for future research. These problems are only just beginning to be addressed (see, for example, Sitti, Aruk, Shintani, & Hashimoto, 2003; Sitti & Hashimoto, 2003).

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Peter F. Hokayem received his B.E. degree in Computer and Communications Engineering from the American University of Beirut, Lebanon in 2001, and an M.S. degree in Electrical Engineering from the University of New Mexico in Albuquerque in 2003. Currently he is pursuing his Ph.D. degree in the Electrical Engineering at the University of Illinois at Urbana-Champaign. His research interests are in the areas of networked control systems, teleoperated systems and nonlinear systems. He is a student member of both the IEEE and SIAM.

Mark W. Spong received the D.Sc. degree in systems science and mathematics in 1981 from Washington University in St. Louis. He has been at the University of Illinois at Urbana-Champaign since 1984 and is currently Donald Biggar Willett Professor of Engineering, Professor of Electrical and Computer Engineering, and Research Professor in the Coordinated Science Laboratory.

Dr. Spong is a Fellow of the IEEE and a member of Phi Beta Kappa. His recent honors include the Senior Scientist Research Award from the Alexander von Humboldt Foundation, the Distinguished Member Award from the IEEE Control Systems Society, and the IEEE Third Millennium Medal. Additional honors include the O. Hugo Schuck and John R. Ragazzini awards from the American Automatic Control Council.

He was the 2005 President of the IEEE Control Systems Society. He has also served as Vice President for Publication Activities of the Control Systems Society from 2000–2002, Editor-in-Chief of the Transactions on Control Systems Technology from 1997–2000, and as an Associate Editor for the Transactions on Automatic Control, the Transactions on Control Systems Technology, the Transactions on Robotics and Automation, and the Control Systems Magazine. He served on the Board of Governors of the Control Systems Society from 1994–2002.

His research interests are in nonlinear control and robotics. He has published over 200 technical articles and is co-author of three books.