ROBOTIC TELEMANIPULATION SYSTEMS: AN OVERVIEW ON CONTROL ASPECTS

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Abstract: Teleoperation systems have been among the first applications of the robotic technology, mainly because of the interest for the nuclear research back in the 50's. Since then, dramatic developments have been achieved, both from the technological point of view (materials, computers, possibility of building miniaturized devices, ...) and from the theoretical one. In this paper, attention is given in particular to the control aspects, and an overview on the main schemes that have been presented in the literature is presented, suggesting some criteria for their analysis and comparison.

Keywords: Telemanipulation systems, Control, Time-Delay Systems

1. INTRODUCTION

Telemanipulation, teleoperation and telerobotics are terms that indicate the capability of a human being of carrying out operations in a remote environment by means of a proper robotic system. As a matter of fact, telemanipulation systems, see (Sheridan, 1989) and (Melchiorri and Eusebi, 1996) for reviews of the historical developments in this field, are of great interest since they permit the interaction with environments that are dangerous or of difficult access for the human beings, e.g. space (Penin, 2000; Sheridan, 1993) or under-sea, or with objects or situations with a different scale with respect to the human typical dimensions, as for example in the case of micro-surgery, see (Moline, 1997) for a survey on the use of telerobotics in health care.

Recently, also Internet has given a relevant impulse to the development of telerobotics since it represents a communication channel available everywhere that can be used to put into communication, although with some limitations, different systems geographically located all over the world, (Goldberg and Siegwart, 2001; Oboe and Fiorini, 1998; Xi and Tarn, 1999; Prokopiou *et al.*, 1999).

A telemanipulator is a complex electro-mechanical system encompassing a *master* (or local) and a *slave* (or remote) device, interconnected by a *communication channel*. The overall system is interfaced on one side (the master) with a *human operator*, and on the other (the slave) with the *environment*, see Fig. 1.

Both master and slave devices have their own local control system, with a very large variety of complexity and sophistication levels, which allow the execution of desired tasks.

There are some features of this kind of manipulators which are not present in an "usual" robotic manipulation system:

1. The presence of a *human operator* for the high-level control of the activities.
2. The presence of a suitable interface to control the system in real time.
3. The need to transmit data between slave and master sides.

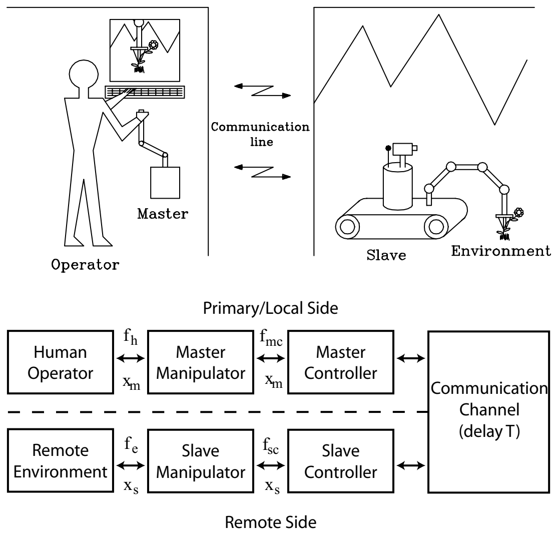

Fig. 1. A telemanipulation system and its block representation. Subscripts m and s refer to variables at the master and slave site respectively.

(4) The presence of a *communication channel*, with limited bandwidth and, possibly, a time-delay.

Usually, the operator specifies a desired velocity ($\dot{x}_m$) to the environment through the master, the communication channel and the slave, and receives back a force signal (f_{md}). If the flow of the signals can be reversed, the operator could specify a force to the environment and receive back a velocity information. This is equivalent to reversing the roles of the master and slave devices. When this operation is possible, the teleoperation system is defined *bilaterally controlled*, (Bejczy and Handlykken, 1981). Besides stability, another important goal of the control system is to have, in steady state, the slave velocity equal to the master velocity, i.e. $\dot{x}_s = \dot{x}_m$, and similarly for the forces, $f_{md} = f_s$. When this is accomplished, the teleoperator is defined *transparent*, (Lawrence, 1993).

From the control point of view, telemanipulation systems have been subject of a number of studies and several control techniques have been applied to (or developed for) these systems. There are different reasons for this relevant interest by the control community: telemanipulators are MIMO nonlinear systems; they present a time-delay between master and slave; they physically interact with the environment; a selection of the type of information transmitted to the operator must be performed, affecting the performances of the overall system; the kinematic configuration and the dimensions of the master and slave robots are not necessarily the same; the physical properties at the remote site are in general not known a priori. All these features represent very interesting challanges that have been approached with different methodological tools.

Note that teleoperators and haptic interfaces present similar control problems, (Burdea, 1996; Salcudean, 1997). As a matter of fact, haptic systems can be considered as particular cases of teleoperators in which the “interaction” at the “remote” part is implemented via software with a virtual reality simulator.

In this paper, a survey on control techniques for telemanipulation robotic systems is given. This survey is followed by the discussion of some criteria that could be used both to analyze the performances of these control schemes and to properly tune their control parameters.

2. CONTROL STRATEGIES

Basic elements of a telemanipulation systems are the presence of a master and a slave systems, the communication channel (and therefore a bandwidth limitation and a possible time delay due to the transmission of information), and the physical interaction of the robots at the slave (and master) site.

In telemanipulation without either force feedback to the operator or a local compliance control, the remote manipulator is strictly controlled according to the master position signal. As a consequence, the system results in being stiff, and errors between the master and slave positions may originate excessive and undesired contact forces.

In bilateral telemanipulation, it has been proved that a profitable manner for increasing system performances (for example in terms of task completion time, total contact time and cumulative contact force) is to reflect back to the operator information about the force applied to the environment. On the other hand, it results that the force reflection gain, i.e. the gain which gives the operator the feeling of the interaction, destabilises the system, especially when time-delays are present. As a matter of fact, in *traditional force reflection* teleoperation, where force reflection is obtained by a direct feedback of the measured force signal, in order to have stability the force reflection gain must be maintained very low, often not sufficient for a significant force feedback.

These basic features have generated a more than relevant quantity of control schemes, proposed in the literature in the last decades, see e.g. (Arcara and Melchiorri, 2002; Arcara, 2002) for an overview. One could observe that, in principle, any control methodology (passivity, variable-structure, small-gain, adaptive, H_∞, ...) has been applied to this challenging field. On the other hand, although the research in this field is very rich, one could observe that there is not a standard solution or approach, neither it is clear what could be considered "the best" control scheme. It could be argued that it is not even clear the definition of a performance criterion by means of which different control schemes can be compared.

In the following, some among the most known control schemes are reported with some details, referring for the sake of simplicity to a SISO linear dynamic model of the master (m) and slave (s) robots:

$$f_m = (m_m s^2 + b_m s)\ x_m \tag{1}$$
$$f_s = (m_s s^2 + b_s s)\ x_s \tag{2}$$

Moreover, it is considered that the forces applied to both the manipulators depend on the "external" interactions (environment and human operator) and on the adopted control scheme. In general, these forces can be written as

$$f_m = f_h - f_{mc} \tag{3}$$
$$f_s = f_e + f_{sc} \tag{4}$$

where f_h, f_e are the forces imposed by the human operator and by the remote environment respectively, while f_{mc}, f_{sc} are the forces computed by the master and slave controllers.

2.1 *Force Reflection (FR)*

This is perhaps the first control scheme appeared in the literature and probably the most intuitive for its simplicity. Position information is transmitted from master to slave, and a force feedback from slave to master is present, (Ferrell, 1965; Ferrell, 1966). The control equations are:

$$\begin{cases} f_{mc} = g_c f_{sd} \\ f_{sc} = k_c(x_{md} - x_s) \end{cases} \tag{5}$$

where g_c, k_c are control parameters. Subscript d indicates the (delayed) signal transmitted in the communication channel:

$$x_{md} = e^{-sT} x_m\ , \qquad f_{sd} = e^{-sT} f_{sc} \tag{6}$$

where e^{-sT} represents the Laplace transformation of the constant delay T in the transmission channel.

Fig. 2 illustrates this control showing both the controllers for master and slave force computation and the variables transmitted in the communication channel.

2.2 *Position Error (PE)*

This is a fully symmetric control scheme, see Fig. 3: the forces applied to the manipulators

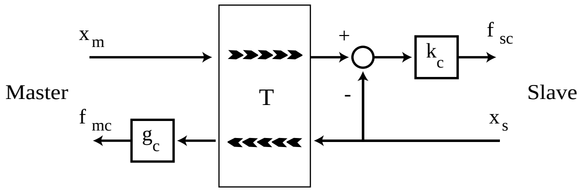

Fig. 2. The Force Reflection scheme.

are proportional to the difference (error) between local position and received (delayed) remote position. In this scheme only position information is thus exchanged between master and slave, (Kim, 1992). The control equations are:

$$\begin{cases} f_{mc} = g_c k_c(x_m - x_{sd}) \\ f_{sc} = k_c(x_{md} - x_s) \end{cases} \tag{7}$$

where g_c, k_c are control parameters. Position information is transmitted between the two sides:

$$x_{md} = e^{-sT} x_m\ , \qquad x_{sd} = e^{-sT} x_s$$

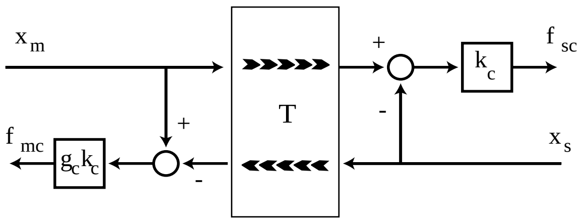

Fig. 3. The Position Error scheme.

2.3 *Shared Compliance Control (SCC)*

Shared compliance control is very similar to the FR scheme, the only difference being a compliance term inserted in the controller at the remote side to modify the behaviour of the slave manipulator according to the interaction with the environment (Kim, 1990; Kim *et al.*, 1992). The control equations become:

$$\begin{cases} f_{mc} = g_c f_{sd} \\ f_{sc} = k_c(x_{md} - x_s + G_f(s) f_e) \end{cases} \tag{8}$$

where g_c, k_c are control parameters and $G_f(s) = \frac{k_f}{1+\tau s}$ represents the transfer function of a low-pass filter with parameters k_f, τ. The information transmitted between the two sides is identical to the FR case:

$$x_{md} = e^{-sT} x_m\ , \qquad f_{sd} = e^{-sT} f_{sc}$$

From Fig. 4 one can appreciate the difference with respect to the FR scheme due to the compliance term, i.e. a filtering action based on the force f_e of the remote environment.

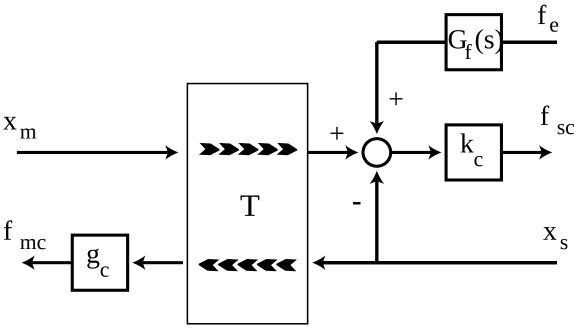

Fig. 4. The Shared Compliance Control scheme.

2.4 *Passive Force Reflection (PFR)*

The FR control scheme, (5), can be modified by adding one or more dissipative elements in order to guarantee the passivity ("damping injection"), (Niemeyer and Slotine, 1991). The control equations become:

$$\begin{cases} f_{mc} = g_c f_{sd} + b_i v_m \\ f_{sc} = k_c \left(\dfrac{v_{md} - f_{sc}/b_i}{s} - x_s \right) \end{cases}$$

where $v_m = s x_m$ represents the velocity of the master and k_c, g_c, b_i are control parameters . The transmitted variables are:

$$v_{md} = e^{-sT} v_m \ , \qquad f_{sd} = e^{-sT} f_{sc}$$

Fig. 5 shows the two dissipative terms with coefficient b_i.

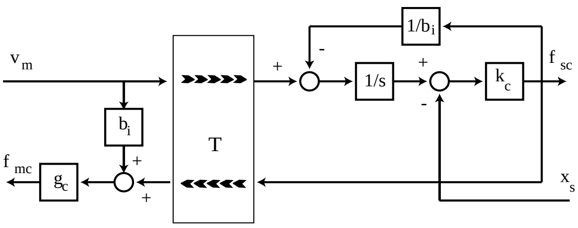

Fig. 5. The Passive Force Reflection scheme.

2.5 *Intrinsically Passive Controller (IPC)*

This scheme is based on passivity concepts. The controller is "built" with passive elements and its implementations can be interpreted in terms of passive physical components such as masses, dampers and springs, see (Arcara *et al.*, 2001; Stramigioli, 2001; Stramigioli *et al.*, 2000) for details. Moreover, scattering variables are used in the communication channel in order to interconnect only passive terms, (Niemeyer and Slotine, 1991; Stramigioli *et al.*, 2002). One of the possible expressions of the control equations is the following:

$$\begin{cases} f_{mc} - f_{mi} = (m_{mc}s^2 + b_{mc}s)x_{mc} \\ f_{mc} = k_{mc}(x_m - x_{mc}) \\ f_{mi} = (k_{mi} + b_{mi}s)(x_{mc} - v_{mi}/s) \\ f_{si} - f_{sc} = (m_{sc}s^2 + b_{sc}s)x_{sc} \\ f_{sc} = k_{sc}(x_{sc} - x_s) \\ f_{si} = (k_{si} + b_{si}s)(v_{si}/s - x_{sc}) \end{cases} \tag{9}$$

where m_{mc}, b_{mc}, k_{mc}, k_{mi}, b_{mi}, m_{sc}, b_{sc}, k_{sc}, k_{si}, b_{si} are the parameters of the controller; x_{mc}, x_{sc} are the positions of the virtual masses implemented in the controllers; f_{mi}, v_{mi}, f_{si}, v_{si} are forces and velocities exchanged between master and slave. The physical interpretation of (9) is shown, for the master, in Fig. 6.

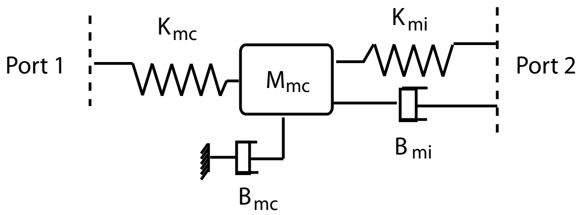

Fig. 6. Scheme of the master IPC: energy is exchanged through port 1 and port 2 with the robot (left) and the transmission channel (right).

In order to guarantee passivity, forces and velocities are transformed in scattering (wave) variables:

$$\begin{cases} S_m^+ = (f_{mi} + b_i v_{mi})/\sqrt{2b_i} \\ S_m^- = (f_{mi} - b_i v_{mi})/\sqrt{2b_i} \end{cases} \begin{cases} S_s^+ = (f_{si} + b_i v_{si})/\sqrt{2b_i} \\ S_s^- = (f_{si} - b_i v_{si})/\sqrt{2b_i} \end{cases} \tag{10}$$

where b_i represents the impedance of the channel. The transmitted variables are

$$S_s^+ = e^{-sT} S_m^+ \ , \qquad S_m^- = e^{-sT} S_s^-$$

Then, by taking into account the causality requirements on the IPC and on the transmission line, one can rewrite (10) to put into evidence the input and output variables, Fig. 7, in the following manner:

$$\begin{cases} S_m^+ = \sqrt{2/b_i} f_{mi} - S_m^- \\ v_{mi} = f_{mi}/b_i - \sqrt{2/b_i} S_m^- \end{cases} \begin{cases} S_s^- = \sqrt{2/b_i} f_{si} - S_s^+ \\ v_{si} = -f_{si}/b_i + \sqrt{2/b_i} S_s^+ \end{cases} \tag{11}$$

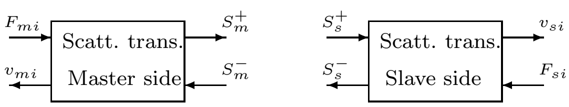

Fig. 7. Scattering transformation at the master and slave side.

2.6 *Four Channels (4C)*

This is a telemanipulation control scheme in which both velocity and force information are exchanged between master and slave, (Lawrence, 1993). The control is defined as:

$$\begin{cases} f_{mc} = -c_6 f_h + c_m v_m + f_{sd} + v_{sd} \\ f_{sc} = c_5 f_e - c_s v_s + f_{md} + v_{md} \end{cases} \tag{12}$$

where $v_m = s x_m$, $v_s = s x_s$ are velocities; c_5, c_6 are feedforward and c_m, c_s feedback control parameters. As concerns the transmitted information, there are four "channels":

$$\begin{array}{ll} v_{md} = c_1 e^{-sT} v_m \ , & f_{sd} = c_2 e^{-sT} f_s \\ f_{md} = c_3 e^{-sT} f_m \ , & v_{sd} = c_4 e^{-sT} v_s \end{array} \tag{13}$$

where c_1, c_2, c_3, c_4 are parameters of the communication line.

In order to simplify the control scheme, one can reduce the number of parameters by setting

$$\begin{array}{ll} c_1 = m_s s + b_s + c_s \ , & c_5 = c_3 - 1 \\ c_4 = -(m_m s + b_m + c_m) \ , & c_6 = c_2 - 1 \end{array} \tag{14}$$

where some of the parameters are defined as 'dynamic' terms in order to achieve perfect transparency, (Hashtrudi-Zaad and Salcudean, 1999), and m_m, m_s, b_m, b_s represent the masses and the damping coefficients of the master and slave manipulators respectively.

This scheme can be simplified, by properly setting the control parameters, obtaining a three-channels scheme (Hashtrudi-Zaad and Salcudean, 1999). In particular, the following control scheme can be obtained from (12), (13) and (14) with $c_2 = 0$:

$$\begin{cases} f_{mc} = f_h + c_m v_m + v_{sd} \\ f_{sc} = (c_3 - 1) f_e - c_s v_s + f_{md} + v_{md} \end{cases}$$

where feedforward actions on f_h, f_e are used. Information is now transmitted in three different channels:

$$v_{md} = c_1 e^{-sT} v_m$$
$$f_{md} = c_3 e^{-sT} f_m \ , \qquad v_{sd} = c_4 e^{-sT} v_s$$

where c_1, c_3, c_4 are free parameters. One can set c_1 and c_4 as specified in (14).

2.7 *Adaptive Motion/Force Control (AMFC)*

As in the four-channels scheme, velocity and force are exchanged in the communication line. Moreover, each manipulator has its own local adaptive position/force control, where the parameters of the manipulator are locally estimated, (Zhu and Salcudean, 1999; Zhu and Salcudean, 2000). The master and slave controllers are:

$$\begin{cases} f_{mc} = -\dfrac{ac}{s+c} G_m(s) f_h + \\ \qquad +(C_m(s) + \dfrac{\lambda}{s} G_m(s)) v_m - f_{sd} - v_{sd} \\ f_{sc} = \dfrac{ac}{s+c} G_s(s) f_e - (C_s(s) + \dfrac{\lambda}{s} G_s(s)) v_s \\ \qquad + f_{md} + v_{md} \end{cases} \tag{15}$$

where a, c, λ are constant parameters; $G_i(s) = \hat{m}_i s + \hat{b}_i + k_i + k_{i1}/s$ and $C_i(s) = k_i + k_{i1}/s$, $i = m, s$, are the feedforward and feedback controllers (k_i, k_{i1} are PI feedback gains); $\hat{m}_i$, $\hat{b}_i$ are the estimated values of the mass and damping parameters of the manipulators (computed online). As concerns the transmitted information, there are four different channels:

$$v_{md} = \frac{c(s+\lambda)}{s(s+c)} G_s(s) e^{-sT} v_m \ , \quad f_{sd} = \frac{ac}{s+c} G_m(s) e^{-sT} f_e$$
$$f_{md} = \frac{ac}{s+c} G_s(s) e^{-sT} f_h \ , \quad v_{sd} = \frac{c(s+\lambda)}{s(s+c)} G_m(s) e^{-sT} v_s$$

2.8 *Sliding-Mode Controller (SMC)*

The variable structure control offers robustness against uncertainties and, moreover, can be used to deal with problems arising with time delay. In (Park and Cho, 1999), a sliding-mode controller is defined at the slave side in order to achieve a perfect tracking in finite time of the delayed master position, while at the master side an impedance controller is used. The corresponding control equations are:

$$\begin{cases} f_{mc} = f_h - b_m v_m + \dfrac{m_m}{m_c}(b_c v_m + k_c x_m - f_h - f_{ed}) \\ f_{sc} = -f_e + b_s v_s + \\ \qquad -\dfrac{m_s}{m_c}(b_c v_{md} + k_c x_{md} - f_{hd} - f_{edd}) + \\ \qquad -m_s \lambda \dot{e} - k_g \ \mathrm{sat}\left(\dfrac{S}{\phi}\right) \end{cases}$$

where m_c, b_c, and k_c are the impedance controller parameters; λ and k_g the sliding-mode parameters; $e = x_s - x_{md}$ is the slave position error; $S = \dot{e} + \lambda e$ the sliding surface; $\mathrm{sat}(\cdot)$ represents the saturation function. Four variables are transmitted from master to slave, and one (f_e) from slave to master:

$$x_{md} = e^{-sT} x_m \ , \qquad v_{md} = e^{-sT} v_m$$
$$f_{hd} = e^{-sT} f_h \ , \qquad f_{edd} = e^{-sT} f_{ed}$$
$$f_{ed} = e^{-sT} f_e$$

2.9 *Predictive Control (PC)*

In the control methods described above, information from the remote site is used as feedback to the master, but no knowledge about the slave dynamics is required in the design of the master controller. Conversely, it is possible to considers explicitly the remote dynamics into the local controller in order to predict the slave behaviour, see (Niemeyer and Slotine, 1991; Sheridan, 1993). The following algorithm for telemanipulation systems, in particular, is based on the well known Smith predictor scheme (Åström and Wittenmark, 1984; Smith, 1957).

Smith predictor is used at the master side in order to anticipate computation of the delayed information from the slave, whereas a simple PD controller is implemented at the slave. This telemanipulation scheme is very similar to the FR one, being the force reflected at the master computed by means of both the predictor and the force feedback from the slave. The controllers are

$$\begin{cases} f_{mc} = g_c \left[\dfrac{(m_s s^2 + b_s s)(b_c s + k_c)}{m_s s^2 + (b_s + b_c)s + k_c} (1 - e^{-2sT}) x_m + f_{sd} \right] \\ f_{sc} = (b_c s + k_c)(x_{md} - x_s) \end{cases} \tag{16}$$

The prediction term is evident in the first expression (master control law). g_c, b_c and k_c are control parameters. The transmitted variables are the same as in the FR scheme:

$$x_{md} = e^{-sT} x_m \ , \qquad f_{sd} = e^{-sT} f_{sc}$$

2.10 *Passive Predictive Control (PPC)*

This method combines the Smith predictor and the scattering variables in order to achieve both the benefits of the performances and stability, (Munir, 2001). Let f_{mc}, v_m, f_{sc}, v_{sr} be forces and velocities exchanged between master and slave. In order to guarantee passivity, these signals are transformed in wave variables, as in (10):

$$\begin{cases} U_m = (f_{mc} + b_i v_m)/\sqrt{2b_i} \\ V_m = (f_{mc} - b_i v_m)/\sqrt{2b_i} \end{cases} \quad \begin{cases} U_s = (f_{sc} + b_i v_{sr})/\sqrt{2b_i} \\ V_s = (f_{sc} - b_i v_{sr})/\sqrt{2b_i} \end{cases}$$

where b_i is the impedance of the channel. The transmitted variables are

$$U_s = e^{-sT} U_m \ , \qquad V_a = e^{-sT} V_s$$

where the signal V_s from the slave becomes the input V_a of the Smith predictor at the master that calculates the wave variable V_m as

$$V_m = \ \text{Regulator}[G_p(s)(1 - e^{-2sT})U_m + V_a] \tag{17}$$

$G_p(s) = V_s/U_s$ represents the transfer function of the entire slave side [1], i.e. the slave manipulator, the PD controller, and the wave transformation; the regulator, see (Munir, 2001) for details, is inserted in order to guarantee passivity; in particular, passivity definition is satisfied since the energy associated with the returning wave V_m is always not greater than the energy associated with the outgoing wave U_m.

The PD controller implemented at the slave is

$$f_{sc} = (b_c s + k_c) \left(\frac{v_{sr} - v_s}{s} \right) \tag{18}$$

where b_c and k_c are parameters.

[1] The transfer function of the slave manipulator with the associated PD controller is defined as $G_s(s) = \dfrac{f_{sc}}{v_{sr}} = \dfrac{(m_s s + b_s)(b_c s + k_c)}{m_s s^2 + (b_s + b_c)s + k_c}$ that, considering the wave transformation, leads to $G_p(s) = \dfrac{V_s}{U_s} = \dfrac{G_s(s) - b_i}{G_s(s) + b_i}$.

3. COMPARISON CRITERIA AND RESULTS

It is of interest to establish general criteria by means of which control schemes for telemanipulation systems can be evaluated and compared. These criteria should consider the performances achieved by the different schemes. In particular, five different aspects are considered here: stability; inertia and damping; tracking; stiffness; drift. Further details concerning the comparison of these and others telemanipulation control schemes, the tuning of the parameters and the maximum performances obtainable with each scheme can be found in (Arcara and Melchiorri, 2002; Arcara, 2002). As shown in these works, stability and performances are always conflictual aspects, and the choice of the control parameters is often the result of a trade-off between them.

CR1. Stability

The stability of a telemanipulation scheme is strongly related to the amount of time delay T in the transmission channel. In practice, one can define two main cases:

(1) **IS** schemes which are *intrinsically stable* (IS), that is stability is automatically guaranteed independently of time delay T.

(2) **PS** schemes which are *possibly stable* (PS), i.e. that can be rendered stable, for any value of the delay T, with a proper choice of the controller's parameters.

Table 1 shows the stability properties of the control schemes summarized in the previous Section. It is worth noticing that four- and three-channels control schemes are usually of PS type but, due to the choice of the control parameters, intrinsic stability independently of time delay T can be achieved (Arcara and Melchiorri, 2002).

CR2. Inertia and Damping

These aspects are related to the perception of the user while moving the master manipulator when the remote arm is not in contact with the environment. In this case, the inertia and damping perceived at the master can be described by means of the following transfer function:

$$G_1(s) \equiv \left(\left. \frac{x_m}{f_h} \right|_{f_e=0} \right)^{-1} \tag{19}$$

In order to compute the inertia and damping, one can rewrite (19) as

$$G_1(s) = m_{eq} s^2 + b_{eq} s + G_1^*(s) \tag{20}$$

where m_{eq}, b_{eq} represent the parameters under consideration (inertia and damping), and $G_1^*(s)$ contains negligible terms of third and higher order, with $\lim_{s \to 0} G_1^*(s)/s^2 = 0$.

	FR	PE	SCC	PFR	IPC	4C	AMFC	SMC	PC	PPC
IS				•	•					•
PS	•	•	•			•	•	•	•	

Table 1. Stability properties of the considered schemes.

Scheme	Inertia (m_{eq})	Damping (b_{eq})
FR	$(1+g_c)m_m - g_c b_m \left(\frac{b_m}{k_c} + 2T\right)$	$(1+g_c)b_m$
PE	$2(m_m - b_m T - k_c T^2) - \frac{b_m^2}{k_c}$	$2(b_m + k_c T)$
SCC	$(1+g_c)m_m - g_c b_m \left(\frac{b_m}{k_c} + 2T\right)$	$(1+g_c)b_m$
PFR	$\left(1 + \frac{g_c b_i^2}{(b_m+b_i)^2}\right) m_m - \frac{2 g_c b_i b_m T}{b_m + b_i} - \frac{g_c b_i^2 b_m^2}{(b_m+b_i)^2 k_c}$	$b_m + b_i + \frac{g_c b_i b_m}{b_m + b_i}$
IPC	$2(m_m + m_{mc}) + b_i T - \frac{(b_m + b_{mc})^2 T}{b_i} + \ldots$ $\ldots - \frac{2 b_{mc}^2 (2k_{mi} + k_{mc}) + 2 b_m (k_{mi} + k_{mc})(b_m + 2b_{mc})}{k_{mi} k_{mc}}$	$2(b_m + b_{mc})$
4C	$\frac{2T(b_m + c_m)}{c_2 + c_3}$	0
AMFC	$\frac{2ak_{m1}(1+cT) + \lambda(-1 - cT + ak_{m1}T)}{2a^2 c k_{m1}}$	$\frac{\lambda(1+cT)}{ac}$
SMC	m_c	b_c
PC	$(1+g_c)m_m - \frac{g_c b_m^2}{k_c}$	$(1+g_c)b_m$
PPC	$2m_m - \frac{b_m^2}{k_c}$	$2b_m$

Table 2. Inertia and damping terms for the considered control schemes.

Table 2 contains the expressions of the perceived inertia m_{eq} and damping b_{eq} for the considered control schemes.

CR3. Tracking

An important property of a telemanipulation system is the ability of the slave device, when it is not in contact with the environment, to track as closely as possible the movements of the master. The tracking properties can be expressed by the following transfer function

$$G_2(s) \equiv \left. \frac{x_m - x_s}{f_h} \right|_{f_e = 0} \tag{21}$$

Also in this case it is convenient to identify a constant term δ, that represents the steady-state error between master and slave positions as a consequence of a unit step of the input force f_h:

$$G_2(s) = \delta \; G_2^*(s) \tag{22}$$

where $G_2^*(s)$ satisfies $G_2^*(0) = 1$ and therefore, in steady state conditions, one obtains $G_2(0) = \delta$.

Table 3 reports the expressions of the tracking error δ for the different schemes. It is important to note that in the PFR case one obtains the velocity error $\delta_v = \frac{b_m}{b_b^2 + b_m^2 + b_b b_m (2 + G_m)}$. As a consequence, the tracking position error is limited only if $b_m = 0$, case in which $\delta = \frac{m_m + b_b T}{b_b^2}$.

CR4. Stiffness

Scheme	Tracking (δ)
FR	$\frac{b_m + k_c T}{b_m k_c (1+g_c)}$
PE	$\frac{1}{2 g_c k_c}$
SCC	$\frac{b_m + k_c T}{b_m k_c (1+g_c)}$
PFR	∞
IPC	$\frac{2b_i(k_{mi} + k_{mc}) + k_{mi} k_{mc} T}{2 b_i k_{mi} k_{mc}}$
4C	$\frac{c_2 - c_3}{2(b_m + c_m)}$
AMFC	0
SMC	0
PC	$\frac{b_m + k_c T}{b_m k_c (1+g_c)}$
PPC	$\frac{b_m + k_c T}{2 b_m k_c}$

Table 3. Tracking errors for the different control schemes.

Another important aspect for the evaluation of the performances of a telemanipulation scheme is the correct perception, for the human operator, of the stiffness of the remote environment. Assuming for example the case of interaction with an environment with known stiffness k_e and damping b_e, the perceived stiffness can be measured with

$$G_3(s) \equiv \left(\left. \frac{x_m}{f_h} \right|_{f_e = -(b_e s + k_e) x_s} \right)^{-1} \tag{23}$$

In this case, one can identify a constant term k_{eq} that represents the perceived stiffness:

$$G_3(s) = k_{eq} G_3^*(s) \tag{24}$$

where $G_3^*(s)$ satisfies $G_3^*(0) = 1$. Table 4 reports the resulting stiffness values for the different schemes. It is worth noticing that, for the PFR scheme, one perceives no stiffness ($k_{eq} = 0$) and only a damping factor equal to $b_{eq} = b_b + b_m + b_b G_m$.

Scheme	Stiffness (k_{eq})
FR	$\frac{k_e g_c k_c}{k_e + k_c}$
PE	$\frac{k_e g_c k_c}{k_e + k_c}$
SCC	$\frac{k_e g_c k_c}{k_e + k_c + k_e k_f k_c}$
PFR	0
IPC	$\frac{k_e b_i k_{mi} k_{mc}}{b_i(k_{mi} k_{mc} + 2k_e(k_{mi} + k_{mc})) + k_e k_{mi} k_{mc} T}$
4C	$\frac{k_e(c_2 + c_3)(b_m + c_m)}{(c_2 + c_3)(b_m + c_m) + 2k_e c_2 c_3 T}$
AMFC	k_e
SMC	$k_e + k_c$
PC	$\frac{k_e g_c k_c}{k_e + k_c}$
PPC	$\frac{k_e k_c (b_i + b_m)}{(k_e + k_c)(b_i + b_m) + 2k_e k_c T}$

Table 4. Perceived stiffness for the control schemes.

CR5. Drift

The last parameter to be evaluated is the position drift between manipulators. This parameter is similar to the tracking error, the only difference being the interaction, at the slave side, with a structured environment with stiffness k_e and damping b_e. The following transfer function is used to evaluate the position drift:

$$G_4(s) \equiv \left. \frac{x_m - x_s}{f_h} \right|_{f_e = -(b_e s + k_e) x_s} \tag{25}$$

Again, one can identify a constant term that represents the position drift between master and slave displacements:

$$G_4(s) = \Delta \; G_4^*(s) \tag{26}$$

where $G_4^*(s)$ satisfies $G_4^*(0) = 1$. Table 5 reports the values of the position drift Δ for the considered control schemes. In the PFR case, one obtains a velocity drift $\Delta_v = \dfrac{1}{b_b + b_m + b_b G_m}$, that in general generates an unlimited position drift.

Scheme	Drift (Δ)
FR	$\frac{1}{g_c k_c}$
PE	$\frac{1}{g_c k_c}$
SCC	$\frac{1 + k_f k_c}{g_c k_c}$
PFR	∞
IPC	$\frac{2b_i(k_{mi} + k_{mc}) + k_{mi} k_{mc} T}{b_i k_{mi} k_{mc}}$
4C	$\frac{2c_2 c_3 T}{(c_2 + c_3)(b_m + c_m)}$
AMFC	0
SMC	0
PC	$\frac{1}{g_c k_c}$
PPC	$\frac{b_i + b_m + 2k_c T}{(b_i + b_m) k_c}$

Table 5. Perceived drift for the control schemes.

4. COMMENTS

Concerning stability, one may observe that only the schemes based on passivity concepts intrinsically guarantee the stability. Regarding the other schemes, as shown in the previous section, the FR, PE and SCC schemes can be made stable with a proper choice of the control parameters, provided that $T < T_{max}$, i.e. only for limited values of time delay. Moreover, in general the maximum admissible delay T_{max} increases from FR to PE and SCC schemes, that is the SCC scheme offers better robustness in terms of stability.

The stability of the AMFC and SMC schemes strongly depends on the remote environment. PC stability is mainly related to a good knowledge of the remote slave manipulator and of the transmission delay T, because of the use of the Smith predictor within its control system.

As mentioned above, each telemanipulation scheme has both positive and negative aspects, and therefore it is hopefully possible to select the control scheme more suitable for the specific application under consideration. Some of the main aspects concerning the choice of a teleoperation scheme are briefly recalled in the following.

The first aspect to be considered is the available information on the transmission time delay T. In fact, the entity of the delay could be “small” (few milliseconds), “medium” (some tenth of second) or “high” (some seconds or more). Furthermore, the delay could be constant or variable (with a certain distribution), known or unknown, and, finally, it could be limited ($T < T_{max}$) or not. This knowledge on the delay T permits to select some telemanipulation schemes and not others because of the stability aspects.

The second aspect to be taken into account is inherent to the desired performances, in terms of tracking properties at the slave manipulator and perception of the environment (correct force feedback). Some specifications have to be defined and taken into account during the design of the control scheme.

A third question is related to the aspects concerning the implementation and the necessary equipment for the development of the telemanipulation controller. Available resources in terms of sensors, computing power, transmission bandwidth and so on are often crucial and they must be considered for the choice of a simple or of a more sophisticated control scheme.

Another important aspect is the knowledge of the environment structure and of the task to be carried out. In fact, the remote environment could be dissipative with no possibility of injecting energy, could have certain damping or stiffness properties, could have a maximum value for the exerted external force or, as extreme case, an operator exerting unpredictable forces could even be connected to the slave manipulator (fully symmetric telemanipulation scheme).

Only by paying attention to these (and other) aspects one can define a suitable telemanipulation scheme for the necessities at hand and, at least, eliminate those that cannot satisfy the given requirements.

5. CONCLUSIONS

In this paper, some among the most known control schemes for telemanipulation robotic systems have been briefly recalled. This overview, besides presenting a "sample" of the wide literature of the field, allows to introduce some criteria for the analysis and comparison of control schemes for telemanipulatios systems. These criteria can also be used for the proper tuning of the parameters characteristic of each scheme, on the basis of the overall design specifications (stability, transparency, perceived stifness, tracking performances, ...).

As a general comment, although the control problem of robotic telemanipulation systems has been addressed in the last decades by a large number of researchers, it may be noticed that it is still a "bottleneck", or at least a problem not solved in a completely satisfactory manner, which limits in some extent a greater diffusion of these systems in more and more applications.

Concerning the known schemes, one can notice that the vast majority discusses only the linear case, "neglecting" in some sense the fact that in reality non linear dynamics are involved. Moreover, very often a "decoupling" assumption is made, i.e. in general only a one-dimensional case is considered. Very few authors have faced the full geometric (3D) problem of these systems, considering the couplings that may arise for example between linear and rotational motions (or forces), (Stramigioli *et al.*, 2002).

Moreover, a problem that seems to be still not completely solved is related to cases in which master and slave devices have different dimensions, and therefore a proper scaling of velocities, forces, impedances is needed. In this sense, also problems related to the estimation/identification of the physical properties (impedance) of the remote object/environment are still not completely solved. How these information can be identified and properly rendered to the operator?

In conclusion, although the very relevant and impressive quantity of research developed in this field, there are questions and aspects that still wait to be solved in a satisfactory manner. For these reasons, telemanipulation will constitute also in the next years a very challanging area for the control (and not only!) community.

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