Robotics and Autonomous Systems 38 (2002) 49–64

Robotics and Autonomous Systems

www.elsevier.com/locate/robot

Control schemes for teleoperation with time delay: A comparative study

Paolo Arcara, Claudio Melchiorri*

Dipartimento di Elettronica Informatica e Sistemistica (DEIS), University of Bologna, Via Risorgimento, 2-40136 Bologna, Italy

Received 2 March 2001; received in revised form 10 August 2001
Communicated by F.C.A. Groen

Abstract

The possibility of operating in remote environments by means of telecontrolled systems has always been considered of relevant interest in robotics. For this reason, in the literature a number of different control schemes has been proposed for telemanipulation systems, based on several criteria such as passivity, compliance, predictive or adaptive control, etc. In each scheme, major concerns have been on one hand the *stability*, which may constitute a problem especially in presence of time delays in the communication channel, and on the other the so-called *transparency* of the overall system. This article aims to compare and evaluate the main features and properties of some of the most common control schemes proposed in the literature, firstly presenting the criteria adopted for the comparative study and then illustrating and discussing the results of the comparison. Moreover, some general criteria will be presented for the selection of the control parameters considering that, due to time delay, a tradeoff between stability and performances has to be made in the selection of these parameters.

Keywords: Bilateral teleoperation; Delayed systems; Force reflection; Intrinsically passive controller; Stability

1. Introduction

During the last decades, different teleoperation systems have been developed to allow human operators to execute tasks in remote or hazardous environments, with a variety of applications ranging from space to underwater, nuclear plants, and so on. For this reason, several control schemes have been proposed in the literature for dealing with the specific problems arising in this area of robotics. In general, main goal of these telemanipulation systems is to execute a task in a remote environment, i.e. via the presence of a master and a slave manipulator and regardless the presence of time delay in the transmission channel between the two manipulators. Besides the obvious requirements of stability, a major concern has always been the so-called *transparency* of the teleoperation scheme, i.e. the achievement of the ideal situation of direct action of the operator on the remote environment, see e.g. [1,2,5,7,11,12,14,17,22].

The control schemes proposed in the literature are based on a number of different techniques, ranging from passivity, compliance, predictive or adaptive control, variable structure, and so on. Every scheme has different aspects that should be considered when

* Corresponding author. Tel.: +39-51-2093034; fax: +39-51-2093073.
E-mail addresses: parcara@deis.unibo.it (P. Arcara), cmelchiorri@deis.unibo.it (C. Melchiorri).

0921-8890/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0921-8890(01)00164-6

designing a telemanipulation system, since the choice of the control algorithm may lead to rather different performances.

This paper, after a review of the main concepts and definitions typical of a telemanipulation system, presents a comparative study of different control techniques known in the literature. In particular, the considered schemes are force reflection; position error; shared compliance control; passivity based force reflection; intrinsically passive controller; four channels architecture; adaptive motion/force control; sliding-mode controller; predictive control and passivity based predictive control, see [3,6,8–10,13,16, 19,20,23] for a detailed presentation. These control schemes have been chosen since they represent a wide range of techniques, and therefore cover a wide variety of the telemanipulation controllers presented in the literature. Therefore, the proposed comparison offers a general overview of the main features and problems connected with the choice of control schemes for telemanipulation.

The criteria considered in this paper for the comparative study of the control schemes concern both stability and performances, [11]. In particular, performances are considered by analyzing the inertia perceived by the operator, the tracking properties, the correct perception of a structured environment and the position drift between the master and slave manipulators. Moreover, the choice of the control parameters in each scheme is discussed with respect to these criteria, suggesting a general method for their definition based on a tradeoff between stability and performance.

The paper is organized as follows. Section 2 reports the definitions and the descriptions of the considered telemanipulation schemes, the master and slave manipulators, the different control systems, and of the information transmitted in the communication channel. Section 3 presents the criteria used to compare the considered control schemes, and Section 4 reports the results. In Section 5, comments and comparisons of the control structures are given and, finally, Section 6 reports some final remarks.

2. Definitions

In this section, a description is given of a master/slave telemanipulation system and of its most relevant features useful for the following analysis. Moreover, the control schemes considered for the comparative study are briefly summarized.

A telemanipulation system may be generically described by means of the block scheme shown in Fig. 1, where the main components and the main variables of relevance for the following considerations are shown.

In particular, the interaction with the human operator on one side and with the environment on the other, the dynamics and the controllers of the master and slave manipulators, and the communication channel characterized by a transmission delay T are schematically illustrated; these are the main components of a telemanipulation systems. In general, the exchanged variables among the blocks in Fig. 1 are position/velocity and force, and each of these blocks can be considered as a two-port dynamic system with a power exchange with the others.

2.1. Dynamics of the master and slave manipulators

The main goal of this paper is to compare in a “standard” situation different control schemes in

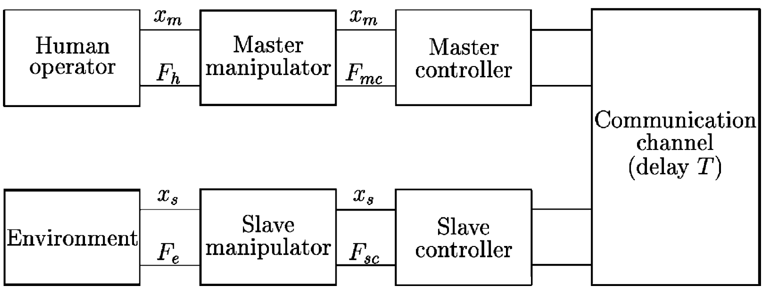

Fig. 1. A teleoperation control scheme.

order to highlight their peculiar features. For this reason, a simple dynamic model for the master and slave systems has been considered. In particular, both the master and slave manipulators are one degree-of-freedom devices, their dynamics is considered linear (e.g. linearized with a proper local controller) and identical systems at both sides have been taken into account. Obviously, these are rather strong assumptions on the dynamics of the master and slave systems, that in general are multi-degrees-of-freedom systems, with different dimensions and dynamic properties. However, as already pointed out, the aim here is to compare the controllers in a clear and simple situation. Finally, a constant transmission delay T in the communication channel is considered. The dynamics of the manipulators can be described by

$$F_{\mathrm{m}} = (M_{\mathrm{m}} s^2 + B_{\mathrm{m}} s) x_{\mathrm{m}}, \qquad F_{\mathrm{s}} = (M_{\mathrm{s}} s^2 + B_{\mathrm{s}} s) x_{\mathrm{s}}, \tag{1}$$

where M_i and B_i are the manipulator's inertia and damping coefficients, while F_i and x_i are the force and the displacement ($i = \mathrm{m, s}$ indicates the master, m, or slave, s, manipulator). For the sake of simplicity, equal values for master and slave inertias and dampers have been considered, i.e. $M_{\mathrm{m}} = M_{\mathrm{s}}$ and $B_{\mathrm{m}} = B_{\mathrm{s}}$ have been assumed.

The forces F_{m} and F_{s} applied to the manipulators depend both on the interaction with the operator/environment and on the control action. In general, these forces can be defined as

$$F_{\mathrm{m}} = F_{\mathrm{h}} - F_{\mathrm{mc}}, \qquad F_{\mathrm{s}} = F_{\mathrm{e}} + F_{\mathrm{sc}}, \tag{2}$$

where F_{h}, F_{e} are the forces imposed by the human operator and by the environment, respectively, while F_{mc}, F_{sc} are the forces computed by the control algorithms.

2.2. Force reflection (FR)

In the force reflection scheme, position information is transmitted from master to slave and force information flows in the opposite direction, see [6]. The control equations are

$$F_{\mathrm{mc}} = G_{\mathrm{c}} F_{\mathrm{sd}}, \qquad F_{\mathrm{sc}} = K_{\mathrm{c}}(x_{\mathrm{md}} - x_{\mathrm{s}}), \tag{3}$$

where G_{c}, K_{c} are proper control parameters. Subscript d indicates a delayed variable related to the information transmitted between the two sides

$$x_{\mathrm{md}} = \mathrm{e}^{-sT} x_{\mathrm{m}}, \qquad F_{\mathrm{sd}} = \mathrm{e}^{-sT} F_{\mathrm{sc}}, \tag{4}$$

where e^{-sT} represents the delay T on the transmission channel.

2.3. Position error (PE)

In the *position error* scheme, the forces applied to the manipulators depend on the position difference (error) between them. Moreover, in this scheme only position information is exchanged in the transmission channel from master to slave and vice versa [9]. The control equations are

$$F_{\mathrm{mc}} = G_{\mathrm{c}} K_{\mathrm{c}}(x_{\mathrm{m}} - x_{\mathrm{sd}}), \qquad F_{\mathrm{sc}} = K_{\mathrm{c}}(x_{\mathrm{md}} - x_{\mathrm{s}}), \tag{5}$$

where G_{c}, K_{c} are control parameters. The information transmitted between the two sides is

$$x_{\mathrm{md}} = \mathrm{e}^{-sT} x_{\mathrm{m}}, \qquad x_{\mathrm{sd}} = \mathrm{e}^{-sT} x_{\mathrm{s}}.$$

2.4. Shared compliance control (SCC)

In this scheme, a "compliance" term is inserted in the slave controller in order to properly modify the desired displacement received from the master side accordingly to the interaction with the environment [10]. The control equations become

$$F_{\mathrm{mc}} = G_{\mathrm{c}} F_{\mathrm{sd}}, \qquad F_{\mathrm{sc}} = K_{\mathrm{c}}(x_{\mathrm{md}} - x_{\mathrm{s}} + G_f(s) F_{\mathrm{e}}), \tag{6}$$

where G_{c}, K_{c} are control parameters and $G_f(s) = K_f/(1 + \tau s)$ represents the transfer function of a low-pass filter with parameters K_f, τ. As in the FR scheme, the information transmitted between the two sides is

$$x_{\mathrm{md}} = \mathrm{e}^{-sT} x_{\mathrm{m}}, \qquad F_{\mathrm{sd}} = \mathrm{e}^{-sT} F_{\mathrm{sc}}.$$

2.5. Force reflection with passivity (FRP)

The FR scheme described by (3) can be modified by a damping injection term in order to guarantee

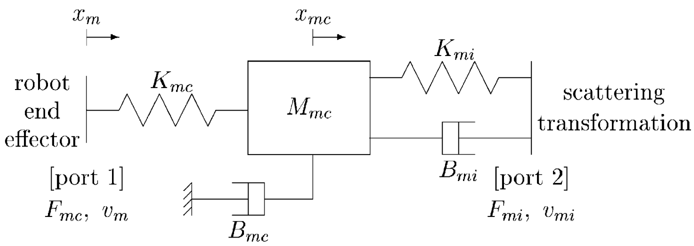

Fig. 2. Conceptual scheme of the master IPC: energy is exchanged through port 1 and port 2 with the robot (left) and the transmission channel (right).

passivity, see e.g. [14]. The control equations become

$$F_{\mathrm{mc}} = G_{\mathrm{c}} F_{\mathrm{sd}} + B_i v_{\mathrm{m}},$$
$$F_{\mathrm{sc}} = K_{\mathrm{c}} \left(\frac{v_{\mathrm{md}} - F_{\mathrm{sc}}/B_i}{s} - x_{\mathrm{s}} \right),$$

where $v_{\mathrm{m}} = s x_{\mathrm{m}}$ represents the velocity of the master and K_{c}, G_{c}, B_i are parameters of the control system. The transmitted variables are

$$v_{\mathrm{md}} = \mathrm{e}^{-sT} v_{\mathrm{m}}, \qquad F_{\mathrm{sd}} = \mathrm{e}^{-sT} F_{\mathrm{sc}}.$$

2.6. *Intrinsically passive controller (IPC)*

This control scheme is based on passivity concepts and in some implementations can be interpreted in terms of passive physical components such as masses, dampers and springs, see [3,19,20] for details. One of these possible forms is the following

$$\begin{aligned}
F_{\mathrm{mc}} - F_{\mathrm{mi}} &= (M_{\mathrm{mc}} s^2 + B_{\mathrm{mc}} s) x_{\mathrm{mc}},\\
F_{\mathrm{mc}} &= K_{\mathrm{mc}} (x_{\mathrm{m}} - x_{\mathrm{mc}}),\\
F_{\mathrm{mi}} &= (K_{\mathrm{mi}} + B_{\mathrm{mi}} s) \left(x_{\mathrm{mc}} - \frac{v_{\mathrm{mi}}}{s} \right),\\
F_{\mathrm{si}} - F_{\mathrm{sc}} &= (M_{\mathrm{sc}} s^2 + B_{\mathrm{sc}} s) x_{\mathrm{sc}},\\
F_{\mathrm{sc}} &= K_{\mathrm{sc}} (x_{\mathrm{sc}} - x_{\mathrm{s}}),\\
F_{\mathrm{si}} &= (K_{\mathrm{si}} + B_{\mathrm{si}} s) \left(\frac{v_{\mathrm{si}}}{s} - x_{\mathrm{sc}} \right),
\end{aligned} \tag{7}$$

where M_{mc}, B_{mc}, K_{mc}, K_{mi}, B_{mi}, M_{sc}, B_{sc}, K_{sc}, K_{si}, B_{si} are parameters; 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. A physical interpretation of the control law (7) is shown in Fig. 2, at least for the master manipulator.

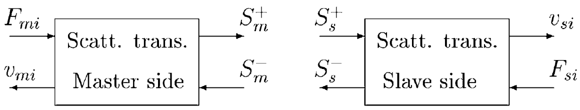

Fig. 3. Scattering transformation at master and slave side.

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

$$\begin{aligned}
S_{\mathrm{m}}^+ &= \frac{F_{\mathrm{mi}} + B_i v_{\mathrm{mi}}}{\sqrt{2B_i}}, \qquad S_{\mathrm{m}}^- = \frac{F_{\mathrm{mi}} - B_i v_{\mathrm{mi}}}{\sqrt{2B_i}},\\
S_{\mathrm{s}}^+ &= \frac{F_{\mathrm{si}} + B_i v_{\mathrm{si}}}{\sqrt{2B_i}}, \qquad S_{\mathrm{s}}^- = \frac{F_{\mathrm{si}} - B_i v_{\mathrm{si}}}{\sqrt{2B_i}},
\end{aligned} \tag{8}$$

where B_i represents the impedance of the channel. As transmitted variables are concerned, one obtains

$$S_{\mathrm{s}}^+ = \mathrm{e}^{-sT} S_{\mathrm{m}}^+, \qquad S_{\mathrm{m}}^- = \mathrm{e}^{-sT} S_{\mathrm{s}}^-.$$

Then, by taking into account the causality requirements on the IPC and on the transmission line, one can rewrite (8) to put in evidence the input and output variables in the following manner:

$$\begin{aligned}
S_{\mathrm{m}}^+ &= \sqrt{\frac{2}{B_i}} F_{\mathrm{mi}} - S_{\mathrm{m}}^-, \qquad v_{\mathrm{mi}} = \frac{F_{\mathrm{mi}}}{B_i} - \sqrt{\frac{2}{B_i}} S_{\mathrm{m}}^-,\\
S_{\mathrm{s}}^- &= \sqrt{\frac{2}{B_i}} F_{\mathrm{si}} - S_{\mathrm{s}}^+, \qquad v_{\mathrm{si}} = -\frac{F_{\mathrm{si}}}{B_i} + \sqrt{\frac{2}{B_i}} S_{\mathrm{s}}^+.
\end{aligned} \tag{9}$$

This definition of input/output variables for the scattering transformation is shown in Fig. 3.

2.7. *Four channels (4C)*

This is a generic telemanipulation control scheme in which both velocity and force information are exchanged between master and slave, see [11]. The control is defined as

$$F_{\mathrm{mc}} = -C_6 F_{\mathrm{h}} + C_{\mathrm{m}} v_{\mathrm{m}} + F_{\mathrm{sd}} + v_{\mathrm{sd}},$$
$$F_{\mathrm{sc}} = C_5 F_{\mathrm{e}} - C_{\mathrm{s}} v_{\mathrm{s}} + F_{\mathrm{md}} + v_{\mathrm{md}}, \tag{10}$$

where $v_{\mathrm{m}} = s x_{\mathrm{m}}$, $v_{\mathrm{s}} = s x_{\mathrm{s}}$ are velocities; C_5, C_6 are feedforward and C_{m}, C_{s} feedback control parameters. As concerns the transmitted information, one obtains four different channels

$$v_{\mathrm{md}} = C_1\, \mathrm{e}^{-sT} v_{\mathrm{m}}, \quad F_{\mathrm{md}} = C_3\, \mathrm{e}^{-sT} F_{\mathrm{m}},$$
$$F_{\mathrm{sd}} = C_2\, \mathrm{e}^{-sT} F_{\mathrm{s}}, \quad v_{\mathrm{sd}} = C_4\, \mathrm{e}^{-sT} v_{\mathrm{s}}, \tag{11}$$

where C_1, C_2, C_3, C_4 are parameters.

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

$$C_1 = M_{\mathrm{s}} s + B_{\mathrm{s}} + C_{\mathrm{s}}, \quad C_4 = -(M_{\mathrm{m}} s + B_{\mathrm{m}} + C_{\mathrm{m}}),$$
$$C_5 = C_3 - 1, \qquad C_6 = C_2 - 1, \tag{12}$$

where some of the parameters are defined as dynamic systems in order to achieve perfect transparency, see [8] for further details.

2.8. Adaptive motion/force control (AMFC)

This control scheme has been proposed in [23]. Each manipulator has its local adaptive position/force controller and position/force tracking command are exchanged in the communication channel between master and slave. The controllers are defined as

$$\begin{aligned} F_{\mathrm{mc}} &= -\frac{AC}{s+C} G_{\mathrm{m}}(s) F_{\mathrm{h}} \\ &\quad + \left(C_{\mathrm{m}}(s) + \frac{\Lambda}{s} G_{\mathrm{m}}(s) \right) v_{\mathrm{m}} - F_{\mathrm{sd}} - v_{\mathrm{sd}}, \\ F_{\mathrm{sc}} &= \frac{AC}{s+C} G_{\mathrm{s}}(s) F_{\mathrm{e}} \\ &\quad - \left(C_{\mathrm{s}}(s) + \frac{\Lambda}{s} G_{\mathrm{s}}(s) \right) v_{\mathrm{s}} + F_{\mathrm{md}} + v_{\mathrm{md}}, \end{aligned} \tag{13}$$

where A, C, Λ are constant parameters; $G_i(s) = \hat{M}_i s + \hat{B}_i + K_i + K_{i1}/s$, $C_i(s) = K_i + K_{i1}/s$, with $i = \mathrm{m, s}$, 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 on-line). As concerns the transmitted information there are four different channels

$$v_{\mathrm{md}} = \frac{C(s+\Lambda)}{s(s+C)} G_{\mathrm{s}}(s)\, \mathrm{e}^{-sT} v_{\mathrm{m}},$$
$$F_{\mathrm{md}} = \frac{AC}{s+C} G_{\mathrm{s}}(s)\, \mathrm{e}^{-sT} F_{\mathrm{h}},$$
$$F_{\mathrm{sd}} = \frac{AC}{s+C} G_{\mathrm{m}}(s)\, \mathrm{e}^{-sT} F_{\mathrm{e}},$$
$$v_{\mathrm{sd}} = \frac{C(s+\Lambda)}{s(s+C)} G_{\mathrm{m}}(s)\, \mathrm{e}^{-sT} v_{\mathrm{s}}.$$

2.9. Sliding-mode controller (SMC)

Sliding-mode control has been successfully applied to telemanipulation schemes. It offers robustness against uncertainties and, moreover, it can be used to deal with time delay.

In [16], a SMC is defined at the slave side in order to achieve a perfect tracking in finite time of the delayed master position, while an impedance controller is used at the master. The corresponding equations are

$$F_{\mathrm{mc}} = F_{\mathrm{h}} - B_{\mathrm{m}} v_{\mathrm{m}} + \frac{M_{\mathrm{m}}}{M_{\mathrm{c}}} (B_{\mathrm{c}} v_{\mathrm{m}} + K_{\mathrm{c}} x_{\mathrm{m}} - F_{\mathrm{h}} - F_{\mathrm{ed}}),$$
$$\begin{aligned} F_{\mathrm{sc}} &= -F_{\mathrm{e}} + B_{\mathrm{s}} v_{\mathrm{s}} - \frac{M_{\mathrm{s}}}{M_{\mathrm{c}}} (B_{\mathrm{c}} v_{\mathrm{md}} + K_{\mathrm{c}} x_{\mathrm{md}} - F_{\mathrm{hd}} - F_{\mathrm{edd}}) \\ &\quad - M_{\mathrm{s}} \lambda \dot{e} - K_g \,\mathrm{sat}\left(\frac{S}{\Phi} \right), \end{aligned}$$

where M_{c}, B_{c}, and K_{c} are the impedance controller parameters; λ and K_g are the SMC parameters; $e = x_{\mathrm{s}} - x_{\mathrm{md}}$ is the position error computed at the slave; $S = \dot{e} + \lambda e$ is the sliding surface to be reached in finite time; $\mathrm{sat}(\cdot)$ represents the saturation function and, finally, subscript d indicates delayed transmitted variables. Four variables are sent from master to slave, and one variable (F_{e}) is sent back in the opposite direction on the communication channel

$$x_{\mathrm{md}} = \mathrm{e}^{-sT} x_{\mathrm{m}}, \qquad v_{\mathrm{md}} = \mathrm{e}^{-sT} v_{\mathrm{m}},$$
$$F_{\mathrm{hd}} = \mathrm{e}^{-sT} F_{\mathrm{h}}, \qquad F_{\mathrm{edd}} = \mathrm{e}^{-sT} F_{\mathrm{ed}},$$
$$F_{\mathrm{ed}} = \mathrm{e}^{-sT} F_{\mathrm{e}}.$$

2.10. Predictive control (PC)

In the control methods described above, information from the slave side is used as feedback to the master, but no a priori knowledge about the slave dynamics is required in the design of the master controller. On the other hand, it is possible to considers explicitly the remote dynamics into the local controller in order to predict the slave behaviour, see [14,17]. The following algorithm for telemanipulation systems, in particular is based on the well known Smith predictor scheme [4,18].

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

$$F_{\mathrm{mc}} = G_{\mathrm{c}}\left[\frac{(M_{\mathrm{s}}s^2 + B_{\mathrm{s}}s)(B_{\mathrm{c}}s + K_{\mathrm{c}})}{M_{\mathrm{s}}s^2 + (B_{\mathrm{s}} + B_{\mathrm{c}})s + K_{\mathrm{c}}}(1 - \mathrm{e}^{-2sT})x_{\mathrm{m}} + F_{\mathrm{sd}}\right], \tag{14}$$

$$F_{\mathrm{sc}} = (B_{\mathrm{c}}s + K_{\mathrm{c}})(x_{\mathrm{md}} - x_{\mathrm{s}}).$$

The prediction term is evident in the first expression (master control law). G_{c}, B_{c} and K_{c} are control parameters. The transmitted information is the same as in the FR scheme

$$x_{\mathrm{md}} = \mathrm{e}^{-sT}x_{\mathrm{m}}, \qquad F_{\mathrm{sd}} = \mathrm{e}^{-sT}F_{\mathrm{sc}}.$$

2.11. Predictive control with passivity (PCP)

Recently, a prediction method combined with wave variables has been presented in the literature [13]. This method enhances the performances with a Smith predictor and, at the same time, maintains passivity by combining prediction and scattering variables.

Let F_{mc}, v_{m}, F_{sc}, v_{sr} be forces and velocities exchanged between master and slave. In order to guarantee passivity, these forces and velocities are transformed in *wave variables*

$$U_{\mathrm{m}} = \frac{F_{\mathrm{mc}} + B_i v_{\mathrm{m}}}{\sqrt{2B_i}}, \quad V_{\mathrm{m}} = \frac{F_{\mathrm{mc}} - B_i v_{\mathrm{m}}}{\sqrt{2B_i}},$$

$$U_{\mathrm{s}} = \frac{F_{\mathrm{sc}} + B_i v_{\mathrm{sr}}}{\sqrt{2B_i}}, \quad V_{\mathrm{s}} = \frac{F_{\mathrm{sc}} - B_i v_{\mathrm{sr}}}{\sqrt{2B_i}},$$

where B_i represents the impedance of the channel. Note that this transformation is the same as in (8). As transmitted variables are concerned, one obtains

$$U_{\mathrm{s}} = \mathrm{e}^{-sT}U_{\mathrm{m}}, \qquad V_a = \mathrm{e}^{-sT}V_{\mathrm{s}},$$

where the signal V_{s} from the slave becomes the input V_a of the Smith predictor at the master that computes the wave variable V_{m} as

$$V_{\mathrm{m}} = \mathrm{Regulator}[G_p(s)(1 - \mathrm{e}^{-2sT})U_{\mathrm{m}} + V_a], \tag{15}$$

$G_p(s) = V_{\mathrm{s}}/U_{\mathrm{s}}$ 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 [13] for details, is inserted in order to guarantee passivity, in particular that 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

$$F_{\mathrm{sc}} = (B_{\mathrm{c}}s + K_{\mathrm{c}})\left(\frac{v_{\mathrm{sr}} - v_{\mathrm{s}}}{s}\right), \tag{16}$$

where B_{c} and K_{c} are parameters.

3. Comparison criteria

The telemanipulation control schemes reported in Section 2 can be analyzed from different points of view. In particular, five different aspects have been considered for their comparison:

1. *Stability* of the telemanipulation scheme as a function of the time delay T.
2. *Inertia and damping* perceived at the master side by the human operator when no force is exerted on the slave manipulator $((x_{\mathrm{m}}/F_{\mathrm{h}})|^{-1}_{F_{\mathrm{e}}=0})$.
3. *Tracking* at the slave side of the master manipulator displacements during movements without interaction $(((x_{\mathrm{m}} - x_{\mathrm{s}})/F_{\mathrm{h}})|_{F_{\mathrm{e}}=0})$.
4. *Stiffness* perceived at the master by the operator in case of interaction with a structured environment at the slave $((x_{\mathrm{m}}/F_{\mathrm{h}})|^{-1}_{F_{\mathrm{e}}=-(B_{\mathrm{e}}s+K_{\mathrm{e}})x_{\mathrm{s}}})$.

[1] The transfer function of the slave manipulator with the associated PD controller is $G_{\mathrm{s}}(s) = F_{\mathrm{sc}}/v_{\mathrm{sr}} = ((M_{\mathrm{s}}s + B_{\mathrm{s}})(B_{\mathrm{c}}s + K_{\mathrm{c}}))/(M_{\mathrm{s}}s^2 + (B_{\mathrm{s}} + B_{\mathrm{c}})s + K_{\mathrm{c}})$ that, considering the wave transformation, leads to $G_p(s) = V_{\mathrm{s}}/U_{\mathrm{s}} = (G_{\mathrm{s}}(s) - B_i)/(G_{\mathrm{s}}(s) + B_i)$.

5. *Drift* of position between master and slave in case of interaction at the slave side $(((x_m - x_s)/F_h)|_{F_e=-(B_e s+K_e)x_s})$.

The ideal telemanipulator should be stable for any value of T, present an inertia as low as possible ($\cong 0$), achieve zero tracking error, display the same stiffness at the master side as the one perceived in the interaction at the slave side, present no position drift.

4. Results

In this section, the results obtained considering the above criteria for the different control schemes are summarized.

4.1. Stability

As stability is concerned, one can enumerate two distinct cases:

1. *IS*: *Intrinsically stable* schemes, i.e. schemes for which stability is guaranteed independently of the time delay T and of the choice of the parameters.
2. *PS*: *Possibly stable* schemes, i.e. schemes that are stable for any time delay T for some choices of the controller's parameters, or stable for $T \leqslant T_{max}$, being T_{max} dependent on the choice of parameters.

Table 1 shows the results concerning the stability of the above control schemes. In particular, notice that the scheme 4C is usually of PS type, but, by choosing some of the control parameters as in (12), IS is achieved with respect to the remaining parameters. More details and explanations about stability of the different telemanipulation schemes are given in the following section. For a more detailed discussion concerning the stability of some of the telemanipulation schemes, see e.g. [5,12].

4.2. Inertia and damping

The inertia and damping perceived by the operator at the master side, when no interaction is present at the slave side, can be evaluated with the following transfer function:

$$G_1(s) \equiv \left(\left. \frac{x_m}{F_h} \right|_{F_e=0} \right)^{-1}. \quad (17)$$

One can rewrite (17) as

$$G_1(s) = M_{eq}s^2 + B_{eq}s + G_1^*(s), \quad (18)$$

where M_{eq}, B_{eq} represent the equivalent inertia and damping perceived at the master and $G_1^*(s)$ contains negligible terms at low frequencies, i.e. terms of the third-order and above, and satisfies $\lim_{s\to 0} G_1^*(s)/s^2 = 0$.

Table 2 reports the expressions of the inertia M_{eq} and damping B_{eq} "perceived" for the different control schemes. Note that, in the SMC scheme, also a stiffness perception appears in the function $G_1(s)$, i.e. a constant term K_c is present in (18) due to the impedance controller.

4.3. Tracking

When no interaction is present, tracking at the slave side of the movement imposed at the master side can be measured by the following transfer function

$$G_2(s) \equiv \left. \frac{x_m - x_s}{F_h} \right|_{F_e=0}.$$

In this case, one can put in evidence a main constant term δ, that represents the steady-state error between the master and slave positions as a consequence of a unit step in F_h:

$$G_2(s) = \delta G_2^*(s),$$

where $G_2^*(s)$ satisfies $\lim_{s\to 0} G_2^*(s) = 1$.

Table 1
Summary of the stability analysis

	FR	PE	SCC	FRP	IPC	4C	AMFC	SMC	PC	PCP
IS				•	•					•
PS	•	•	•			•	•	•	•	

Table 2
Perceived inertia and damping

Scheme	Inertia (M_{eq})	Damping (B_{eq})
FR	$(1+G_{\mathrm{c}})M_{\mathrm{m}} - G_{\mathrm{c}}B_{\mathrm{m}}\left(\dfrac{B_{\mathrm{m}}}{K_{\mathrm{c}}}+2T\right)$	$(1+G_{\mathrm{c}})B_{\mathrm{m}}$
PE	$2(M_{\mathrm{m}} - B_{\mathrm{m}}T - K_{\mathrm{c}}T^2) - \dfrac{B_{\mathrm{m}}^2}{K_{\mathrm{c}}}$	$2(B_{\mathrm{m}}+K_{\mathrm{c}}T)$
SCC	$(1+G_{\mathrm{c}})M_{\mathrm{m}} - G_{\mathrm{c}}B_{\mathrm{m}}\left(\dfrac{B_{\mathrm{m}}}{K_{\mathrm{c}}}+2T\right)$	$(1+G_{\mathrm{c}})B_{\mathrm{m}}$
FRP	$\left(1+\dfrac{G_{\mathrm{c}}B_i^2}{(B_{\mathrm{m}}+B_i)^2}\right)M_{\mathrm{m}} - \dfrac{2G_{\mathrm{c}}B_iB_{\mathrm{m}}T}{B_{\mathrm{m}}+B_i} - \dfrac{G_{\mathrm{c}}B_i^2B_{\mathrm{m}}^2}{(B_{\mathrm{m}}+B_i)^2K_{\mathrm{c}}}$	$B_{\mathrm{m}}+B_i+\dfrac{G_{\mathrm{c}}B_iB_{\mathrm{m}}}{B_{\mathrm{m}}+B_i}$
IPC	$2(M_{\mathrm{m}}+M_{\mathrm{mc}}) + B_iT - \dfrac{(B_{\mathrm{m}}+B_{\mathrm{mc}})^2T}{B_i} + \cdots$ $- \dfrac{2B_{\mathrm{mc}}^2(2K_{\mathrm{mi}}+K_{\mathrm{mc}}) + 2B_{\mathrm{m}}(K_{\mathrm{mi}}+K_{\mathrm{mc}})(B_{\mathrm{m}}+2B_{\mathrm{mc}})}{K_{\mathrm{mi}}K_{\mathrm{mc}}}$	$2(B_{\mathrm{m}}+B_{\mathrm{mc}})$
4C	$\dfrac{2T(B_{\mathrm{m}}+C_{\mathrm{m}})}{C_2+C_3}$	0
AMFC	$\dfrac{2AK_{\mathrm{m1}}(1+CT)+\Lambda(-1-CT+AK_{\mathrm{m1}}T)}{2A^2CK_{\mathrm{m1}}}$	$\dfrac{\Lambda(1+CT)}{AC}$
SMC	M_{c}	B_{c}
PC	$(1+G_{\mathrm{c}})M_{\mathrm{m}} - \dfrac{G_{\mathrm{c}}B_{\mathrm{m}}^2}{K_{\mathrm{c}}}$	$(1+G_{\mathrm{c}})B_{\mathrm{m}}$
PCP	$2M_{\mathrm{m}} - \dfrac{B_{\mathrm{m}}^2}{K_{\mathrm{c}}}$	$2B_{\mathrm{m}}$

Table 3 reports the values of δ. Note that, in the FRP case, one obtains the velocity tracking error $\delta_v = B_{\mathrm{m}}/(B_i^2+B_{\mathrm{m}}^2+B_iB_{\mathrm{m}}(2+G_{\mathrm{c}}))$; therefore, the tracking position error is limited only if $B_{\mathrm{m}}=0$, and its value is $\delta=(M_{\mathrm{m}}+B_iT)/B_i^2$. Moreover, for the SMC, in case the parameter K_{c} is set to 0 (choice that improves the perceived stiffness, as shown below) one obtains $\delta = T/B_{\mathrm{c}}$.

Table 3
Tracking capabilities

Scheme	Tracking (δ)
FR	$\dfrac{B_{\mathrm{m}}+K_{\mathrm{c}}T}{B_{\mathrm{m}}K_{\mathrm{c}}(1+G_{\mathrm{c}})}$
PE	$\dfrac{1}{2G_{\mathrm{c}}K_{\mathrm{c}}}$
SCC	$\dfrac{B_{\mathrm{m}}+K_{\mathrm{c}}T}{B_{\mathrm{m}}K_{\mathrm{c}}(1+G_{\mathrm{c}})}$
FRP	∞
IPC	$\dfrac{2B_i(K_{\mathrm{mi}}+K_{\mathrm{mc}})+K_{\mathrm{mi}}K_{\mathrm{mc}}T}{2B_iK_{\mathrm{mi}}K_{\mathrm{mc}}}$
4C	$\dfrac{C_2-C_3}{2(B_{\mathrm{m}}+C_{\mathrm{m}})}$
AMFC	0
SMC	0
PC	$\dfrac{B_{\mathrm{m}}+K_{\mathrm{c}}T}{B_{\mathrm{m}}K_{\mathrm{c}}(1+G_{\mathrm{c}})}$
PCP	$\dfrac{B_{\mathrm{m}}+K_{\mathrm{c}}T}{2B_{\mathrm{m}}K_{\mathrm{c}}}$

4.4. *Stiffness*

The stiffness parameter represents the force perception at the master side when the slave interacts with an environment. Although more complex models for the interaction could be easily adopted, here the environment has been considered modeled by a stiffness K_{e} and a damping B_{e}. A measure of the stiffness perceived at the master side can be given by means of the following transfer function:

$$G_3(s) \equiv \left(\left.\frac{x_{\mathrm{m}}}{F_{\mathrm{h}}}\right|_{F_{\mathrm{e}}=-(B_{\mathrm{e}}s+K_{\mathrm{e}})x_{\mathrm{s}}}\right)^{-1}.$$

Table 4
Stiffness and drift analysis results

Scheme	Stiffness (K_{eq})	Drift (Δ)
FR	$\frac{K_e G_c K_c}{K_e + K_c}$	$\frac{1}{G_c K_c}$
PE	$\frac{K_e G_c K_c}{K_e + K_c}$	$\frac{1}{G_c K_c}$
SCC	$\frac{K_e G_c K_c}{K_e + K_c + K_e K_f K_c}$	$\frac{1 + K_f K_c}{G_c K_c}$
FRP	0	∞
IPC	$\frac{K_e B_i K_{mi} K_{mc}}{B_i(K_{mi}K_{mc} + 2K_e(K_{mi} + K_{mc})) + K_e K_{mi} K_{mc} T}$	$\frac{2B_i(K_{mi} + K_{mc}) + K_{mi}K_{mc}T}{B_i K_{mi} K_{mc}}$
4C	$\frac{K_e(C_2 + C_3)(B_m + C_m)}{(C_2 + C_3)(B_m + C_m) + 2K_e C_2 C_3 T}$	$\frac{2C_2C_3T}{(C_2 + C_3)(B_m + C_m)}$
AMFC	K_e	0
SMC	$K_e + K_c$	0
PC	$\frac{K_e G_c K_c}{K_e + K_c}$	$\frac{1}{G_c K_c}$
PCP	$\frac{K_e K_c(B_i + B_m)}{(K_e + K_c)(B_i + B_m) + 2K_e K_c T}$	$\frac{B_i + B_m + 2K_c T}{(B_i + B_m)K_c}$

Again, one can try to identify a main constant term K_{eq} which represents the stiffness perceived at the master:

$$G_3(s) = K_{eq} G_3^*(s),$$

where $G_3^*(s)$ satisfies $\lim_{s\to 0} G_3^*(s) = 1$. Table 4 reports the results. Note that in the FRP case one perceives no stiffness ($K_{eq} = 0$) and a damping term with value $B_i + B_m + B_i G_c$.

4.5. *Drift*

Finally, the drift between master and slave has been evaluated when an interaction is present with a remote environment, with stiffness K_e and damping B_e. The following transfer function has been defined to evaluate the position drift:

$$G_4(s) \equiv \left.\frac{x_m - x_s}{F_h}\right|_{F_e = -(B_e s + K_e)x_s}.$$

One can define a main constant term which represents the position drift at low frequencies

$$G_4(s) = \Delta G_4^*(s),$$

where $G_4^*(s)$ satisfies $\lim_{s\to 0} G_4^*(s) = 1$. Table 4 shows the different values Δ of the position drift. In the FRP scheme one obtains the velocity tracking error $\delta_v = 1/(B_i + B_m + B_i G_c)$, that leads to an infinite position drift.

5. Comparison and comments

As stability is concerned, one can observe that only the schemes based on passivity guarantee intrinsic stability. Regarding the other schemes, the FR, PE and SCC 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, i.e. the SCC scheme offers better robustness in terms of stability. Stability of the AMFC and SMC schemes strongly depends on the external environment. PC stability is mainly related to a good knowledge of the remote slave manipulator and transmission delay T because of the use of the Smith predictor.

5.1. *Tuning of the parameters*

5.1.1. *Force reflection*

From Tables 2–4, one may conclude that ideal values for the control parameters in (3) are $K_c \gg 0$,

$G_c = 1$. Note that this choice leads to: (1) values of the inertia and damping perceived at the master double with respect to the single manipulator case (for $T \ll 1$); (2) a tracking error $\delta = T/2B_m$ depending on the delay; (3) a correct stiffness perception (almost the same as the environment); (4) negligible position drift. Obviously, as mentioned above, problems arise when dealing with the stability of this scheme. As a matter of fact, the maximum admissible delay T_{max} for which stability is achieved decreases as K_c increases. Therefore, K_c has to be tuned as a tradeoff between stability and performance requirements. This compromise gives, in practical examples, results worse than the ideal ones. In fact, the characteristic equation of the FR scheme, obtained from (1)–(4) is

$$G(s, T) = M_m s^2 + B_m s + K_c + G_c K_c \,e^{-2sT}. \quad (19)$$

In order to study the stability of the system described by (19), one can apply, for example, the analytic stability test presented in [21], obtaining the following equation

$$\begin{aligned}\tilde{G}(s, \tilde{T}) = {} & K_c + G_c K_c + (B_m + 2K_c\tilde{T} - 2G_c K_c \tilde{T})s \\ & + (M_m + 2B_m\tilde{T} + K_c\tilde{T}^2 + G_c K_c \tilde{T}^2)s^2 \\ & + (2M_m\tilde{T} + B_m\tilde{T}^2)s^3 + M_m\tilde{T}^2 s^4, \quad (20)\end{aligned}$$

where the maximum admissible delay T_{max} in the communication channel, necessary to guarantee stability, is related to the values of the variables ω, $\tilde{T}$ associated with the imaginary roots $s = \mathrm{j}\omega$ of (20) via the following equation

$$T_{max} = \min_{\omega_0, T_0 > 0} \left(\frac{1}{\omega_0}[\arg(1 + \mathrm{j}\omega_0 T_0) - \arg(1 - \mathrm{j}\omega_0 T_0)] \bigg|_{\tilde{G}(\mathrm{j}\omega_0, T_0) = 0} \right),$$

where ω_0 and T_0 express the values of the solutions of $\tilde{G}(\mathrm{j}\omega, \tilde{T}) = 0$. In fact, one can consider that for $\tilde{T} = 0$ all the roots of (20) have negative real part and assuming that a T_0 exists such that one of the roots of (20) becomes unstable (with positive real part), then T_0 can be determined by the Routh criterion checking when an element of the associated column array becomes negative. In this specific case, all the entries of the Routh column array are positive with the exception of the fourth one that, after simple algebraic manipulations, reduces to

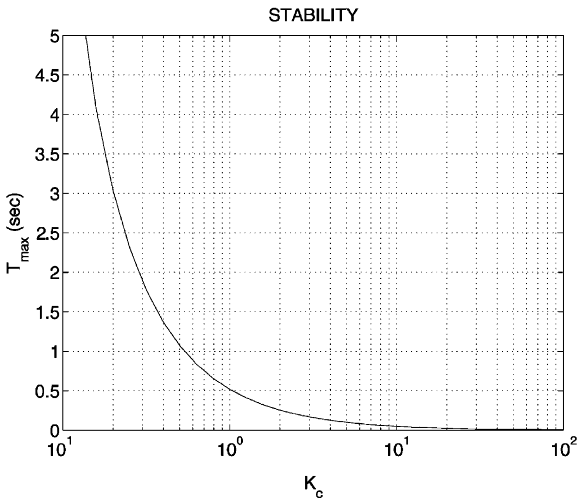

Fig. 4. Maximum time delay allowed for the FR scheme in function of the parameter K_c.

$$\begin{aligned}R_4(\tilde{T}) = {} & 2(B_m^3\tilde{T}^2 + 2B_m^2\tilde{T}(M_m + (1 - G_c)K_c\tilde{T}^2) \\ & - 4G_c K_c M_m \tilde{T}(M_m - (1 - G_c)K_c\tilde{T}^2) \\ & + B_m(M_m^2 + 2(1 - 2G_c)K_c M_m \tilde{T}^2 \\ & + (1 - G_c^2)K_c^2\tilde{T}^4)).\end{aligned}$$

Therefore, by testing the condition $R_4(\tilde{T}) = 0$ one obtains T_0. Then, by using (20) again, one determines the frequency ω_0 of the corresponding imaginary solution to be used in computing T_{max}.

As concern numerical values for the parameter K_c, setting $G_c = 1$ and considering, as a benchmark in this paper, $M_m = M_s = 10$ and $B_m = B_s = 1$ in (1), one obtains the following characteristic equation

$$G(s, T) = 10s^2 + s + K_c + K_c \,e^{-2sT} \quad (21)$$

By studying the stability of (21), one can obtain the maximum admissible delay T_{max} in the communication channel, as a function of parameter K_c, that guarantees the stability of the control scheme. The results are presented in Fig. 4 and summarized in Table 5. Note that these values for T_{max} have been obtained

Table 5
Maximum communication delays admissible for the FR scheme

K_c	< 0.05	0.1	1	10	100
T_{max}	∞	7.854	0.517	0.050	0.005

with $F_e = 0$, larger values could be obtained by considering interactions with an external passive environment (with proper parameters B_e and K_e).

If a low value of K_c is chosen, due to stability problems, it could easily happen that the environment stiffness K_e is larger than K_c. In this case, a bad perception of the remote stiffness is obtained, since $K_{eq} = (K_e G_c K_c)/(K_e + K_c) \neq K_e$.

5.1.2. Position error

The parameters G_c, K_c in (5) should be chosen in the following manner: $G_c = 1$ for symmetry of the master and slave controllers, and K_c as large as possible ($K_c \gg 0$) according to the value of T, for possible inertia and damping perception problems, in order to obtain: (1) values of perceived inertia and damping doubled with respect to the inertia and damping of the master; (2) a low tracking error; (3) an almost correct stiffness perception; (4) negligible position drift.

Also in this case a main problem is the stability, since as the control parameters increase stability is no more guaranteed. In fact, one can compute the maximum admissible delay T_{max} in the communication channel in order to maintain the stability of the control scheme. For example, by choosing $G_c = 1$ and setting $M_m = M_s = 10$ and $B_m = B_s = 1$ in (1), one obtains the following characteristic equation

$$G(s, T) = (10s^2 + s + K_c)^2 - K_c^2\, e^{-2sT}. \tag{22}$$

Table 6
Maximum communication delays admissible in the PE scheme

K_c	< 0.05	0.1	1	10	100	1000
T_{max}	∞	15.708	1.035	0.100	0.010	0.001

By applying the previous stability test to (22), one obtains the maximum admissible delay T_{max} reported in Table 6 as function of the parameter K_c. One can observe that, also in this case, for $K_c < 0.05$ the system described by (22) is stable independently of delay T.

Since, because of stability, low values of K_c have to be selected, unacceptable results can be obtained in terms of tracking, stiffness and drift. The following figures show the tradeoff between stability and performances. From Fig. 5, one can observe that the minimization of both $1/T_{max}$ (left) and Δ (right) leads to incompatible values of K_c. In fact, acceptable values for both transmission delay ($T_{max} > 200$–300 ms) and position drift ($\Delta < 1$–10 mm) lead to disjoint ranges for K_c. Fig. 6 shows different stiffness perception (K_{eq}), in the two cases $K_c = 5$ (left) and $K_c = 100$ (right), as a function of the environment properties (i.e. K_e).

As stated above for the FR scheme, also in this case the values of the admissible time delay T_{max} (computed with $F_e = 0$) are increased in case of interaction with the external environment (B_e and K_e).

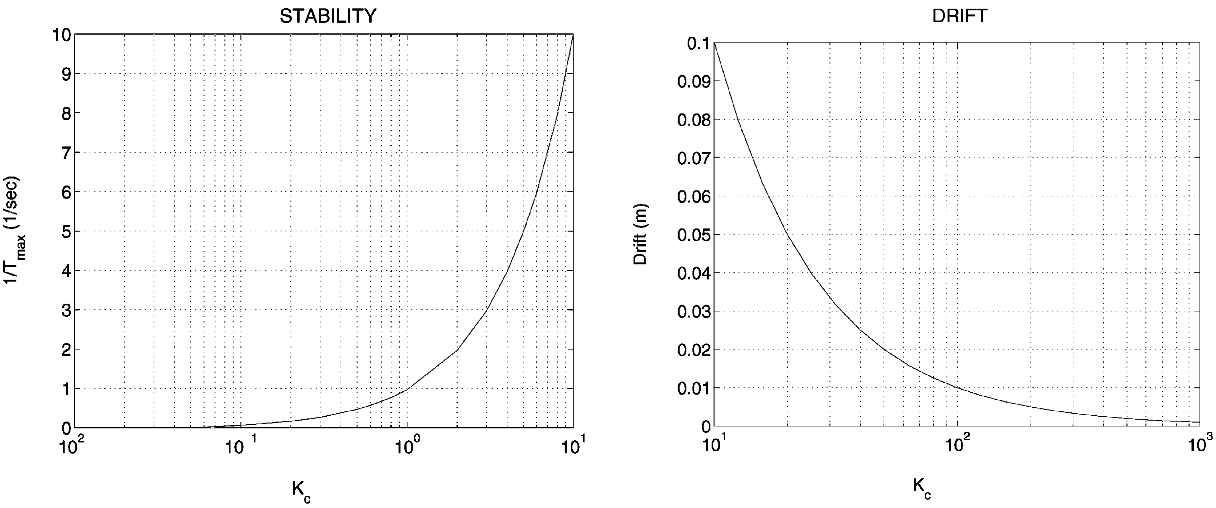

Fig. 5. Stability (left) and position drift (right) properties of the PE scheme.

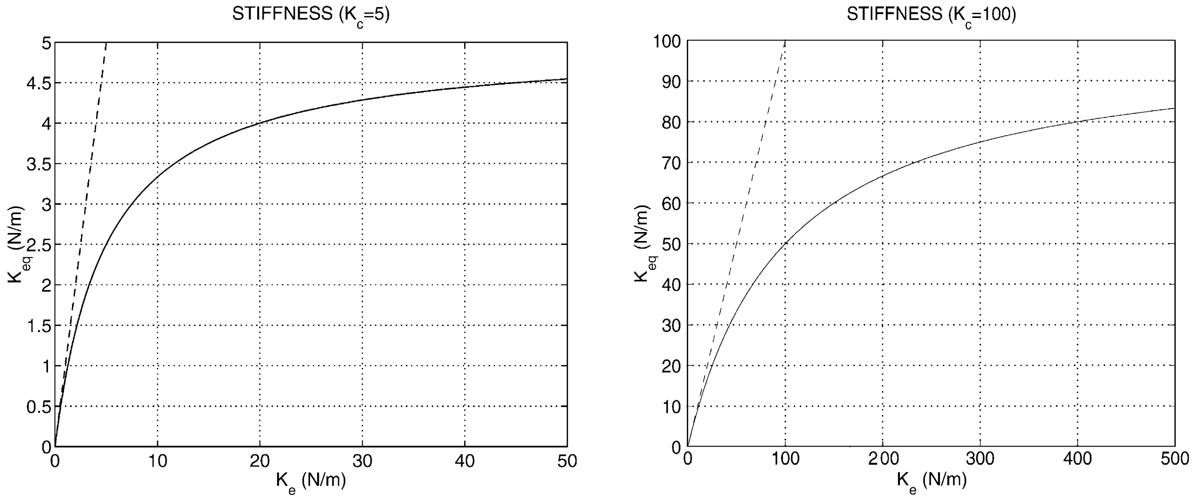

Fig. 6. Stiffness perception K_{eq} on varying the environment stiffness K_e for two values of parameter: $K_c = 5$ (left), $K_c = 100$ (right). The ideal stiffness ($K_{eq} = K_e$) is shown with dashed lines.

5.1.3. Shared compliance control

Parameters in (6) can be set as follows: $G_c = 1$, $K_c \gg 0$, $K_f = 0$; note that using the local compliance control the perceived stiffness is altered and a position drift is introduced. The following values are thus obtained: (1) perceived inertia and damping doubled with respect to the master for $T \ll 1$; (2) tracking error depending on the delay $\delta = T/2B_m$; (3) correct stiffness perception; (4) no position drift. In fact, by choosing $K_f \neq 0$, a correct stiffness perception cannot be obtained anymore, since the remote compliance control modifies the perception of the environment.

As shown in [10], this scheme can improve stability aspects in two possible manners: (1) the filter $G_f(s)$ can be modeled in order to slightly increase K_c, with a fixed T_{max} and with respect to the FR scheme, thus increasing the tracking performances; (2) G_c can be set to 0 (no force feedback to the operator), in order to avoid instability, in the case that transmission delay T is too high, maintaining good tracking (mainly due to some kind of visual feedback for the operator) and good interaction with the environment at the slave side because of the compliance control.

5.1.4. Force reflection with passivity

This scheme guarantees passivity, and therefore stability, for any value of the parameters. Unfortunately, it is not efficient in terms of performances. In fact, due to the damping injection B_i, unavoidable position tracking error and drift are introduced and stiffness perception is not allowed with this telemanipulation scheme.

5.1.5. Intrinsically passive controller

By choosing in (7) the parameters $K_{mc} = K_{sc} \gg 0$, $K_{mi} = K_{si} \gg 0$ for symmetry and $B_{mi} = B_i$ to avoid wave reflections, one obtains: (1) a double perceived inertia increased by the virtual inertia of the controller and analogous damping term for $T \ll 1$; (2) a tracking error $\delta = T/2B_i$ depending on delay; (3) a stiffness perception similar to the environment stiffness and depending on delay; (4) a position drift $\Delta = T/B_i$. In this case, there are no problems connected with stability issues, because of the passivity of the whole telemanipulation control scheme, so parameters can be set without any constraint due to stability.

5.1.6. Four channels

By properly setting the parameters (considered as dynamic systems), perfect transparency can be obtained in the case the time delay is null, e.g. $C_m = K_c/s$, see [11]. In this case, one can obtain: (1) zero perceived inertia and zero damping at the master side; (2) a zero tracking error; (3) a stiffness perception equal to the environment stiffness; (4) no position drift. Problems arise as time delay is involved. In fact, perfect transparency is no more guaranteed if $T \neq 0$, and only a tradeoff between different performance requirements can be achieved. For example, parameter C_m should be limited or set to 0 due to the inertia perception at the master side.

5.1.7. Adaptive motion/force control

This telemanipulation scheme achieves perfect transparency as shown in [23], and one can obtain: (1) small perceived inertia and damping at the master side; (2) a zero tracking error; (3) a stiffness perception equal to the environment stiffness; (4) no position drift. Problems arise when a time delay $T \neq 0$ is present. In fact, stability is not guaranteed a priori in this case. In [23], it has been shown that stability is always achieved in case of free motion $F_e = 0$ and, furthermore, that small values of A and large values of C in (13) maintain stability, for every time delay T, for a certain range of the damping and stiffness (B_e, K_e) of the external environment. Parameters $\hat{M}_i$, $\hat{B}_i$, K_i, K_{i1} should be set equal for the two manipulators ($i = \mathrm{m, s}$) for the symmetry of the scheme; in addition an algorithm for on-line estimations of $\hat{M}_i$, $\hat{B}_i$ must be implemented in the controllers.

5.1.8. Sliding-mode controller

The parameters M_c, B_c, and K_c of the master controller can be set to achieve the desired impedance. By setting $K_c = 0$ (i.e. the perceived stiffness is the one of the environment) and tuning λ and Φ, choosing the dynamics of the tracking error and the boundary layer of the sliding mode, one obtains: (1) a desired perceived inertia M_c and damping B_c; (2) a tracking error T/B_i, depending on delay; (3) a correct stiffness perception; (4) a zero position drift.

In order to compare this scheme with the previous ones, one can set $M_c = M_m$, $B_c = B_m$, and $K_c = 0$ at the master controller.

This SMC guarantees an ideal delayed tracking between master and slave positions, but in presence of structured environments (F_e as a function of x_s, v_s), it easily turns out to be unstable. In fact, this scheme is IS for $F_e = 0$, otherwise it becomes very similar to the FR, with the following characteristic equation

$$G(s, T) = M_c s^2 + B_c s + K_c + (B_e s + K_e)\,\mathrm{e}^{-2sT}.$$

Using the previous benchmark ($M_c = M_m = 10$, $B_c = B_m = 1$ and $K_c = 0$) this control leads to a master manipulator identical to the one considered in both the FR and PE schemes. Moreover, if T_{max} is the maximum time delay to maintain stability, the following considerations hold: (1) T_{max} decreases as K_e increases with a fixed B_e; (2) T_{max} initially increases and then decreases as B_e increases with a fixed K_e.

Table 7
Maximum admissible communication delays with the SMC scheme ($B_e = 0.5$)

K_e	1	10	100
T_{max}	0.750	0.075	0.007

Table 8
Maximum admissible communication delays with the SMC scheme ($K_e = 1$)

B_e	0.01	0.1	1	10	100	1000
T_{max}	0.513	0.558	0.969	0.785	0.079	0.008

Tables 7 and 8 show the values for T_{max} as a function of K_e and B_e, with respectively B_e constant and K_e constant. Fig. 7 shows T_{max} as a function of both K_e and B_e.

5.1.9. Predictive control

This control scheme is very similar to the FR one, being the only difference, the fact that the Smith predictor computes the force feedback in advance by using the current master position. Ideal parameters in (14) are $K_c \gg 0$, $G_c = 1$, which lead to identical results with respect to the FR scheme: (1) a double perceived inertia and damping; (2) a tracking error depending on delay $T/2B_m$; (3) a correct stiffness perception (the same as the environment); (4) no position drift.

As stability is concerned, two main problems are given by: (1) the time delay error in the Smith predictor; (2) the external forces acting at the slave. In fact, $G_c \ll 1$ is necessary to guarantee stability of the closed loop function due to error in the knowledge of the time delay T, see [15] for details, thus reducing benefits of an high K_c in correct stiffness perception and position drift. Furthermore, the possible interaction with the environment and the presence of the force F_e, that depends on x_s and v_s, introduce a delayed term in the closed loop function that cannot be compensated by the Smith predictor, and this leads to a limited time delay T_{max} in order to guarantee stability.

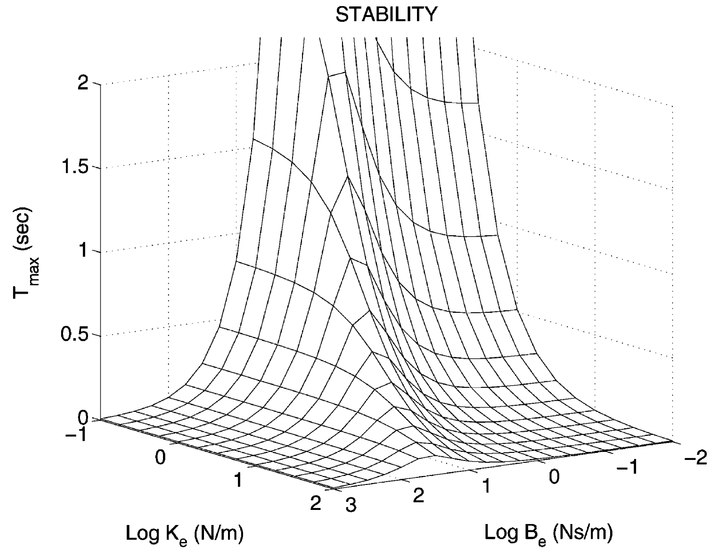

Fig. 7. Stability properties of the SMC scheme as a function of parameters K_e and B_e.

For example, using $M_m = 10$, $B_m = 1$ as in the previous schemes, and $K_c = 100$, $B_c = 10$, $G_c = 1$ for the controller's parameters and assuming perfect knowledge of the time delay T, the results shown in Fig. 8 are obtained. These results are given in function of the stiffness K_e and of the damping B_e in the external force F_e. Tables 9 and 10 summarize results for B_e constant and K_e constant.

5.1.10. *Predictive control with passivity*

Ideal values for slave controller parameters in (16) are $K_c \gg 0$ to achieve good performance and $B_c = B_i$

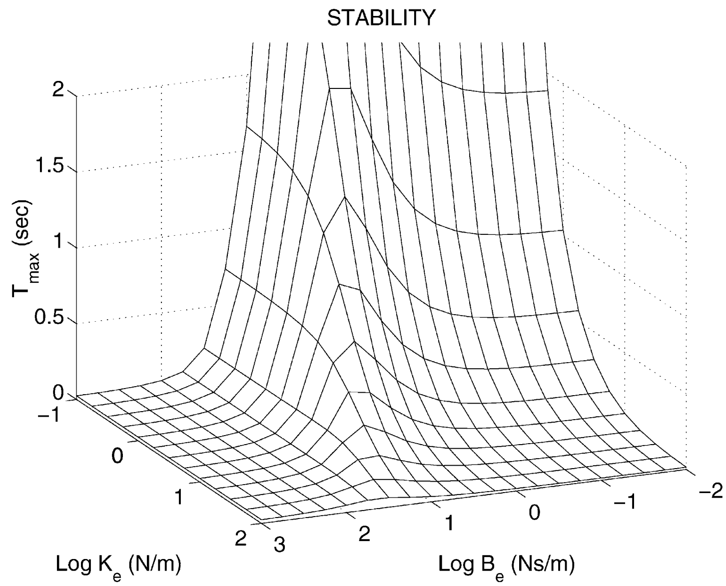

Fig. 8. Stability properties of the PC scheme as a function of parameters K_e and B_e.

Table 9
Maximum admissible communication delays in the PC scheme ($B_e = 0.5$)

K_e	1	10	100
T_{max}	1.270	0.120	0.016

Table 10
Maximum admissible communication delays in the PC scheme ($K_e = 1$)

B_e	0.01	0.1	1	10	100	1000
T_{max}	1.034	1.078	1.493	1.473	0.054	0.024

to avoid wave reflections. In this case, one obtains the following results, very similar to the IPC scheme: (1) a double perceived inertia and damping; (2) a tracking error depending on delay $T/2B_m$; (3) a stiffness perception also depending on delay; (4) a position drift which tends to $2T/(B_i + B_m)$.

This scheme guarantees passivity, and thus stability, because of the choice of transmitting the wave variables on the communication channel. Main limit of this control system is the impossibility to transmit power from environment to the master manipulator, via the slave. In fact, power transmission is only allowed from the operator to the environment and not vice versa, due to the particular regulator in (15).

5.2. Considerations

As described 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 application under consideration. Here, the main aspects concerning the project/choice of a teleoperation scheme are briefly recalled.

The first aspect to be considered is the information available on the transmission delay T. In fact, the delay could be very small (few milliseconds), medium (some tenths of a second) or high (some seconds or more). Moreover, it could be constant or variable (with a certain distribution) and, furthermore, it could be limited (T_{max}) or not. This knowledge of the delay permits to select some telemanipulation schemes and not others because of 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).

A third question is related to the aspects concerning the implementation and the equipment available for the development of the telemanipulation controller. In fact, depending on the available resources (sensors, computing power, transmission bandwidth, and so on) it may be convenient the choice of a simple or a more sophisticated control scheme.

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

Only by paying attention to all these aspects, one can choose a telemanipulation scheme suitable for the necessities at hand and, immediately, eliminate those that cannot satisfy the general initial requirements.

6. Conclusion and future work

In this paper, a comparative study of several telemanipulation control schemes has been presented. The study has been carried out considering different points of view. Both stability and performances have been analyzed, with specific attention in particular to the perceived inertia, the tracking error, the perceived stiffness and the position drift. Different parameters of each telemanipulation scheme have been discussed and defined and the overall performances have been evaluated.

Future works will concern the study of multi-degrees-of-freedom and nonlinear teleoperation systems, the definition of further indexes of comparison for telemanipulation schemes, as well as specific considerations about time-varying transmission delays.

Acknowledgements

This work has been supported by MISTRAL, a project funded by MURST, Ministero dell'Università e della Ricerca Scientifica e Tecnologica. P. Arcara thanks the *Progetto Giovani Ricercatori* of the University of Bologna.

References

[1] R.J. Anderson, M.W. Spong, Bilateral control of teleoperators with time delay, IEEE Transactions on Automatic Control 34 (5) (1989) 494–501.

[2] R.J. Anderson, M.W. Spong, Asymptotic stability for force reflecting teleoperators with time delay, International Journal of Robotics Research 11 (2) (1992) 135–149 .

[3] P. Arcara, C. Melchiorri, S. Stramigioli, Intrinsically passive control in bilateral teleoperation MIMO systems, in: European Control Conference, ECC'01, Porto, Portugal, September 2001.

[4] K.J. Aström, B. Wittenmark, Computer-Controlled Systems, Prentice-Hall, Englewood Cliffs, NJ, 1984.

[5] A. Eusebi, Sistemi di teleoperazione bilaterale di posizione e forza in presenza di ritardi, Ph.D. Thesis, DEIS, University of Bologna, 1995.

[6] W.R. Ferrell, Delayed force feedback, IEEE Transactions on Human Factors in Electronics 8 (1966) 449–455.

[7] B. Hannaford, Stability and performance tradeoffs in bi-lateral telemanipulation, in: IEEE International Conference on Robotics and Automation, ICRA'89, Scottsdale, AZ, May 1989, pp. 1764–1767.

[8] K. Hashtrudi-Zaad, S.E. Salcudean, On the use of local force feedback for transparent teleoperation, in: IEEE International Conference on Robotics and Automation, ICRA'99, Detroit, MI, May 1999, pp. 1863–1869.

[9] W.S. Kim, Developments of new force reflecting control schemes and an application to a teleoperation training simulator, in: IEEE International Conference on Robotics and Automation, ICRA'92, Nice, France, May 1992, pp. 1412–1419.

[10] W.S. Kim, B. Hannaford, A.K. Bejczy, Force-reflection and shared compliant control in operating telemanipulators with time delay, IEEE Transactions on Robotics and Automation 8 (2) (1992) 176–185.

[11] D.A. Lawrence, Stability and transparency in bilateral teleoperation, IEEE Transactions on Robotics and Automation 9 (5) (1993) 624–637.

[12] C. Melchiorri, A. Eusebi, Telemanipulation: System aspects and control issues, in: C. Melchiorri, A. Tornambè (Eds.), Modelling and Control of Mechanisms and Robots, World Scientific, Singapore, 1996, pp. 149–183.

[13] S. Munir, Internet-based teleoperation, Ph.D. Thesis, G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, February 2001.

[14] G. Niemeyer, J.E. Slotine, Stable adaptive teleoperation, International Journal of Oceanic Engineering 16 (1) (1991) 152–162.

[15] Z. Palmor, Stability properties of smith dead-time compensator controllers, International Journal of Control 32 (6) (1980) 937–949.

[16] J.H. Park, H.C. Cho, Sliding-mode controller for bilateral teleoperation with varying time delay, in: IEEE International Conference on Advanced Intellectual Mechanics, AIM'99, Atlanta, GA, September 1999, pp. 311–316.

[17] T.B. Sheridan, Space teleoperation through time delay: review and prognosis, IEEE Transactions on Robotics and Automation 9 (5) (1993) 592–606.

[18] O.J.M. Smith, Closer control of loops with dead time, Chemical Engineering Progress 53 (5) (1957) 217–219.

[19] S. Stramigioli, Modeling and IPC control of interactive mechanical systems—a coodinate-free approach, Lecture Notes in Control and Information Science, Springer, Berlin, 2001.

[20] S. Stramigioli, A. van der Schaft, B. Maschke, S. Andreotti, C. Melchiorri, Geometric scattering in tele-manipulation of port controlled Hamiltonian systems, in: Conference on Decision and Control, CDC'00, Sydney, Australia, December 2000.

[21] A. Thowsen, An analytic stability test for a class of time-delay systems, IEEE Transactions on Automatic Control 26 (3) (1981) 735–736.

[22] Y. Yokokohji, T. Yoshikawa, Bilateral control of master–slave manipulators for ideal kinesthetic coupling—formulation and experiment, IEEE Transactions on Robotics and Automation 10 (5) (1994) 605–620.

[23] W.H. Zhu, S.E. Salcudean, Stability guaranteed teleoperation: an adaptive motion/force control approach, IEEE Transactions on Automatic Control 45 (11) (2000) 1951–1969.

Paolo Arcara was born in Como, Italy in 1972. He received the Laurea degree in Automatic Engineering from the Politecnico of Milan in 1997. He is currently a Ph.D. student at the Dipartimento di Elettronica Informatica e Sistemistica at the University of Bologna, Italy. His current research interests focus on the control of telemanipulation systems, Hamiltonian systems and haptic interfaces. He received the Giorgio Quazza award for the best Master's thesis in Automatic Engineering in 1998, with his thesis on control of vibrations in helicopters.

Claudio Melchiorri was born on October 23, 1959. He received the Laurea degree in Electrical Engineering in 1985, and the Ph.D. in 1990 both at the University of Bologna. He has been appointed as "Adjunct Associate in Engineering" at the Department of Electrical Engineering, University of Florida, Gainesville, FL, in 1988 and as "Visiting Scientist" at the Artificial Intelligence Laboratory, MIT, Cambridge, MA, USA, for periods in 1990 and 1991. Since 1985, he has been with DEIS, the Department of Electrical Engineering, Computer Science and Systems of the University of Bologna, working in researches in the field of robotics and automatic control. He currently holds the position of Full Professor in Robotics at the University of Bologna. He is author or coauthor of more than 100 scientific papers presented at conferences or published in journals, of three books on digital control, and is coeditor of four books on robotics. His research interests include dexterous robotic manipulation, haptic interfaces, telemanipulation systems, advanced sensors for robotic applications, nonlinear control.