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INTRINSICALLY PASSIVE CONTROL IN BILATERAL TELEOPERATION MIMO SYSTEMS

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Abstract

In the literature, a number of interesting control schemes has been proposed for telemanipulation robotic systems. Because of the intrinsically non constant and large time delay, due to the communication channel, passivity has been largely used in these schemes in order to achieve stability of the overall teleoperation system. In this paper, the application to this context of a control scheme based on the equivalence with passive physical systems is discussed. This scheme allows to achieve stability and good performances also in cases where the time-delay is not constant. Moreover, the multi-dimensional case is taken into account, considering tasks in which not only linear motions/forces are present but also rotations and torques. Simulation results are presented and discussed.

1 Introduction

It is well known that bilateral teleoperation implies a two-way information exchange between the master and slave robotic systems. In particular, the human operator can perceive the environment and monitor the task execution via force feedback transmitted from the slave. On the other hand, the force feedback may destabilize the overall system if proper control schemes are not adopted. A consequence is that there is a sort of natural trade-off in telemanipulation between stability and transparency, [6, 9, 10]. Several control schemes have been proposed in the literature in order to obtain good performances from the teleoperation system, see [4] for an overview on various control approaches. As stability aspects are concerned, most of the proposed controllers are based on passivity in order to guarantee stability, assuming that the environment does not inject energy in the system, see e.g. [1, 2, 13]. As regards transparency, different approaches have been proposed in order to achieve good performances, i.e. to let the human operator perceive the same impedance as seen at the environment on the slave system, see e.g. [3, 7, 8, 11, 20].

In this paper a passivity approach for telemanipulation systems is presented. The controller is based on the so-called *Intrinsically Passive Control* (IPC), [12, 16, 17], and it is applied to a MIMO case that considers both linear and rotational variables. In particular, since multidimensional springs and dampers are required in the definition of an IPC for this case, the approach originally presented in [5] and reformulated in [16] is adopted for the problem at hand.

This paper is organized as follows. Section 2 briefly recalls the main definitions about passivity, scattering variables and families of spatial compliance and damping. Section 3 presents the control scheme based on the IPC concepts. Section 4 reports and discusses some simulation results with two 3-dof planar manipulators, while Section 5 concludes with final remarks.

2 Definitions

Passivity. A multi-dimensional mechanical system with *velocity* vector v and *force* vector f is *passive* if the following equation holds

$$E(t_1) \leq E(t_0) + \int_{t_0}^{t_1} f^T(\tau) v(\tau) d\tau \qquad (1)$$

where $E(\cdot) \geq 0$ represents the *energy* stored in the system, $f^T v = P(\cdot)$ is the supplied *power* and $t_0 < t_1$ are different time instants. This equation states that internal creation of energy is not admissible for passive systems. Equation (1) can be written in a differential form as

$$\frac{dE(t)}{dt} = P(t) - P_{diss}(t) \qquad (2)$$

where $P_{diss}(\cdot) \geq 0$ represents the dissipated power.

Energy is related to the state of the system and since a passive system is characterized by an energy function bounded from below, the system is always marginally stable. Furthermore, if dissipation is present everywhere, there will always be asymptotically stable equilibrium positions. Finally, by shaping the internal energy of the system, it is possible to change these stable positions to some desired one.

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An important property of passive systems is that *interconnection of passive systems* leads to a passive system.

Scattering Variables. In a teleoperation scheme, because of delays in communication, the signals to be transmitted in the communication channel have to be properly defined in order to guarantee stability for the whole system. *Scattering variables*, [13], represent a powerful way to maintain passivity (and therefore stability) in the communication channel, independently on the time delay in data transmission.

The basic idea is to transmit a proper combination of velocities and forces instead of the velocity and force signals v and f. At each side of the channel, one can compute the value to be transmitted with a two input/two output algebraic system: inputs are the scattering variable coming from the opposite side and the local velocity, outputs are the scattering variable to be sent to the opposite side and the local force.

At each side of the bilateral telemanipulation system, the scattering variables are defined as

$$S^+ = \frac{f + b\,v}{\sqrt{2b}} \qquad S^- = \frac{f - b\,v}{\sqrt{2b}} \tag{3}$$

where b represents the characteristic impedance of the communication line. Note that S^+ is the transmitted scattering variable, while S^- is the received one.

An important result associated to scattering variables is that the power flow can be expressed as an algebraic sum of two "powers" depending only on the two scattering variables:

$$P = f^T v = \frac{1}{2}||S^+||^2 - \frac{1}{2}||S^-||^2 \tag{4}$$

Spatial Compliance and Damping Families. In dealing with multiple degrees of freedom, it is useful to introduce, as shown in [5], two *spatially affine impedance families* with compliance and damping properties. These families represent, in fact, passive systems and will be used in the telemanipulation control scheme. Using the notation presented in [5], one can define:

1) *Spatial Compliance Family*

$$G_C = \begin{bmatrix} R_r\tilde{m}_o & K_t\Delta p \\ 0^T & 0 \end{bmatrix} \in \mathbb{R}^{4\times4}$$

with $\Delta p = p_r - p_v$, $\tilde{m}_o = \Lambda_o R_v^T R_r - R_r^T R_v \Lambda_o$, $K_t = R_t \Gamma_t R_t^T$, where p and R represent position vectors and orientation matrices; subscripts r and v indicate, respectively, the robot end effector and the virtual equilibrium (reference).

R_t, p_v, R_v, Γ_t and Λ_o are the parameters of the family.

2) *Spatial Damping Family*

$$G_D = \begin{bmatrix} R_r\tilde{m}'_o & B_t\Delta \dot{p} \\ 0^T & 0 \end{bmatrix} \in \mathbb{R}^{4\times4}$$

where $\Delta\dot{p} = R_r v_r - R_v v_v$ (v represents velocities in the local frame), $\tilde{m}'_o = (\tilde{\omega}_r - \tilde{\omega}_v)\hat{\Lambda}_o + \hat{\Lambda}_o(\tilde{\omega}_r - \tilde{\omega}_v)$ ($\tilde{\omega}$ is an antisymmetric matrix defined with angular velocity ω), $B_t = \hat{R}_t\hat{\Gamma}_t\hat{R}_t^T$.

$\hat{R}_t$, v_v, $\tilde{\omega}_v$, R_v, $\hat{\Gamma}_t$ and $\hat{\Lambda}_o$ are the parameters of the family.

As discussed in [5], it is possible to define wrenches W (forces and moments) with the following correspondences:

$$G_C = \begin{bmatrix} R_r\tilde{m}_o & K_t\Delta p \\ 0^T & 0 \end{bmatrix} \rightarrow W_C = \begin{bmatrix} R_r^T K_t \Delta p \\ m_o \end{bmatrix} \tag{5}$$

$$G_D = \begin{bmatrix} R_r\tilde{m}'_o & B_t\Delta \dot{p} \\ 0^T & 0 \end{bmatrix} \rightarrow W_D = \begin{bmatrix} R_r^T B_t \Delta \dot{p} \\ m'_o \end{bmatrix} \tag{6}$$

where m_o, m'_o are vectors containing the elements of the antisymmetric matrices $\tilde{m}_o$, $\tilde{m}'_o$.

3 The Control Scheme

The main idea here is to connect the two robots of a bilateral telemanipulator with a control system that guarantees passivity. This is obtained by using an Intrinsically Passive Controller (IPC), that can be interpreted as composed by physical objects (such as springs, masses and dampers, guaranteeing physical dissipativity), and scattering variables for the transmission on the communication channel. In such a way, all the elements of this scheme (manipulators, controllers and transmission channel, as well as human operator and remote environment) are passive, guaranteeing the overall stability. Fig. 1 shows the bilateral telemanipulation scheme. This problem has been recently considered in [18] also in the general framework of port-controlled Hamiltonian systems.

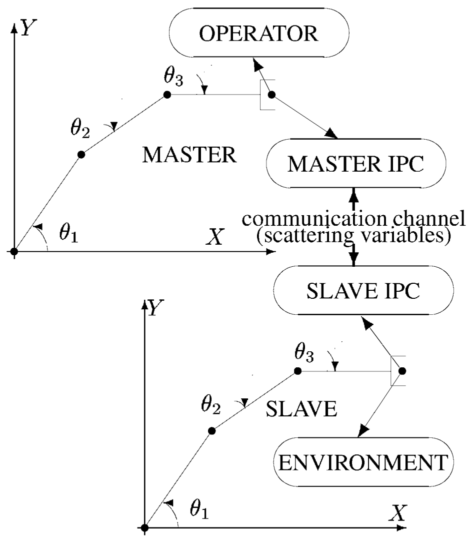

Figure 1: Telemanipulation control scheme.

IPC Definition. Fig. 1 shows that an IPC for both the master and the slave robots is defined. Each controller has the structure illustrated in Fig. 2, where it is represented by 'physical' mechanical elements M_c, k_c, k_v, b_c, b_v, corresponding to a virtual mass, two springs and two dampers respectively. The scheme of Fig. 2 is a physical interpretation of the control algorithm, that "interacts" with the robot and the communication line by means of the force/velocity signals at port 1 and port 2. The basic idea is that the dynamics of mass M_c is simulated in the control algorithm, subject to the forces of the springs and of the dampers. Then, the 'control' action is applied to both the master and slave side through ports 1 and 2. Note that this control scheme is an extension to the telemanipulation case of similar control structures already successfully applied to robotic manipulation, see e.g. [12, 17].

An additional difference, with respect to other telemanipulation schemes, is that here both linear and rotational displacements are simultaneously considered and therefore springs k_c, k_v and dampers b_c, b_v must be defined consequently, as discussed in the previous Section, (5), (6).

In particular, since a relatively simple case with two 3-dof planar manipulators is considered in the following Section, (5) (spatial springs) simplifies to

$$W_C = \begin{bmatrix} F_{xy} \\ M_\theta \end{bmatrix} = \begin{bmatrix} K_t \begin{bmatrix} p_{ax} - p_{bx} \\ p_{ay} - p_{by} \end{bmatrix} \\ \Lambda_o \sin(p_{a\theta} - p_{b\theta}) \end{bmatrix} \tag{7}$$

where F_{xy} is the force on the plane, M_θ represents the moment, K_t, Λ_o are parameters and subscripts a, b indicate the two reference frames connected by the spring. Note that the sine function derives from the general definition of $\tilde{m}_o$. The above equation describes both the springs k_c and k_v.

As far as dampers are concerned, from (6) one obtains

$$W_D = \begin{bmatrix} F_{xy} \\ M_\theta \end{bmatrix} = \begin{bmatrix} B_t \begin{bmatrix} \dot{p}_{ax} - \dot{p}_{bx} \\ \dot{p}_{ay} - \dot{p}_{by} \end{bmatrix} \\ \hat{\Lambda}_o(\dot{p}_{a\theta} - \dot{p}_{b\theta}) \end{bmatrix} \tag{8}$$

where B_t, $\hat{\Lambda}_o$ are parameters. Eq. (8) represents both the dampers b_c and b_v.

As already mentioned, two equivalent IPCs have been defined for the master and the slave side, see Fig. 2. Port 1 is directly "connected" to the robot end effector (master or, respectively, slave) and the spring k_c determines the control force input f_{IPC} of the IPC to be applied to the manipulator. Port 2 is "connected" to the opposite robot (slave or, respectively, master) via scattering variables in the communication channel, and spring k_v is associated with the force to be transmitted via this port. Damper b_v is important for *impedance matching* with the characteristic impedance of the communication channel b, see e.g. [18], while b_c is used for *damping injection*, [15].

Finally, the control torque τ_m (τ_s) applied to the master (slave) manipulator is computed from the force f_{IPC} generated by the spring k_c as:

$$\begin{aligned} \tau_m &= J^T(q) f_{IPC} = J_m^T(q) W_C(k_c) \\ &= J^T(q) \begin{bmatrix} K_t(k_c) \begin{bmatrix} p_{rx} - p_{Mx} \\ p_{ry} - p_{My} \end{bmatrix} \\ \Lambda_o(k_c) \sin(p_{r\theta} - p_{M\theta}) \end{bmatrix} \end{aligned} \tag{9}$$

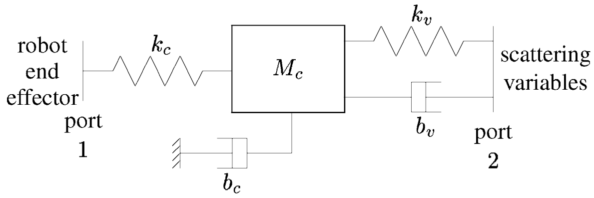

Figure 2: Physical interpretation of an intrinsically passive controller (master and slave IPC).

where J is the Jacobian matrix of the master (slave) manipulator, $W_C(k_c)$, $K_t(k_c)$, $\Lambda_o(k_c)$ represent the wrench and the parameters associated with spring k_c. Subscripts r and M indicate the master (slave) end effector and the virtual mass M_c.

4 Simulation Results

Master/Slave Manipulators. In order to test the control scheme, a symmetric bilateral manipulation scheme has been simulated, based on two 3-dof planar robots. In Tab. 1, the Denavit-Hartemberg and the dynamic parameters, expressed in the International Units (kg, m, s), are reported; r_{xyz} represents the position of the center of mass, M and I are the mass and the inertia of each link respectively.

Link	α	a	θ	d	M	r_x	r_y	r_z	I
1/2/3	0	1	0	0	1	-0.5	0	0	0.0833

Table 1: Denavit-Hartemberg and dynamic parameters of the planar three DOF manipulator.

The dynamic model of the manipulator can be written in the usual matrix form

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} = \tau + J^T(q) f_{ext} \tag{10}$$

where $q = [\theta_1, \theta_2, \theta_3]^T$ is the joint position vector, $M(\cdot)$ is the inertia matrix, $C(\cdot, \cdot)$ contains the Coriolis and centrifugal terms, τ is the input torque vector, $J(\cdot)$ is the Jacobian matrix and f_{ext} is the force applied to the robot by the human operator or by the environment. The gravitational term $g(q)$ is not present since the manipulators are considered in an horizontal plane. The control torque vector τ is computed as in (9).

The forward kinematic is

$$\begin{cases} p_{rx} &= a_1 C_1 + a_2 C_{12} + a_3 C_{123} \\ p_{ry} &= a_1 S_1 + a_2 S_{12} + a_3 S_{123} \\ p_{r\theta} &= \theta_1 + \theta_2 + \theta_3 \end{cases}$$

that represents the spatial displacement (p_{rx}, p_{ry}) and the orientation $p_{r\theta}$ of the end effector, being as usual $C_i = \cos(\theta_i)$, $S_i = \sin(\theta_i)$.

Communication Channel. The scattering transformation at

Parameters	M_c		k_c		k_v		b_c		b_v	
	Mass	Inertia	K_t	Λ_o	K_t	Λ_o	B_t	$\hat{\Lambda}_o$	B_t	$\hat{\Lambda}_o$
Value	0.1	0.1	$\begin{matrix} 500 & 0 \\ 0 & 500 \end{matrix}$	500	$\begin{matrix} 500 & 0 \\ 0 & 500 \end{matrix}$	500	$\begin{matrix} 10 & 0 \\ 0 & 10 \end{matrix}$	10	$\begin{matrix} 10 & 0 \\ 0 & 10 \end{matrix}$	10

Table 2: IPC parameters for both the master and slave controllers.

the master side is

$$\begin{cases} S_m^+ = \sqrt{\frac{2}{b}} f_m - S_m^- \\ v_m = \frac{f_m}{b} - \sqrt{\frac{2}{b}} S_m^- \end{cases} \tag{11}$$

where the input $S_m^-(t) = S_s^+(t-T)$ is the output scattering variable at the slave side with the time delay T, f_m is the force at the communication port with the master IPC, and b is the characteristic impedance of the line; the outputs are the scattering variable $S_m^+(t)$ sent to the slave and the master manipulator velocity v_m. In fact, as this particular example is concerned, velocities and forces are replaced with generalized twists and wrenches. This scattering transformation is shown in Fig. 3.

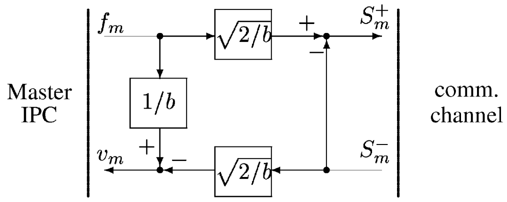

Figure 3: Scattering transformation at the master side.

Similarly, the equations for the slave side can be written as

$$\begin{cases} S_s^+ = -\sqrt{\frac{2}{b}} f_s - S_s^- \\ v_s = \frac{f_s}{b} + \sqrt{\frac{2}{b}} S_s^- \end{cases} \tag{12}$$

where $S_s^-(t) = S_m^+(t-T)$, f_s is the force at the communication port with the slave manipulator IPC and the differences in the signs between (11) and (12) are due to the fact that we consider $v_m \to -v_s$ and $f_m \to -f_s$ in the telemanipulation scheme.

Summarizing, f_m, v_m and f_s, v_s are the power variables exchanged at the port between the IPC and the communication channel (at the master and slave side respectively).

As shown in [13], *impedance matching* is necessary in order to avoid wave reflections in the communication channel. This means that the damper b_v of the IPC, see Fig. 2, must be equal to the parameter b of the scattering transformation in (3), (11), (12).

Intrinsically Passive Controllers. Due to the symmetry of the telemanipulation system, also the IPCs at the master and slave side have been configured with the same structure, Fig. 2, and the same values, reported in Tab. 2. Due to the above mentioned impedance matching problem one has to choose $b = 10$ as characteristic impedance of the transmission line.

Simulations. Two types of simulations have been carried out:

1) a desired trajectory is imposed at the master by the human operator without interaction with the environment (*free space* movement)

2) a motion is imposed with an interaction with an obstacle at the slave side (*structured environment* perception)

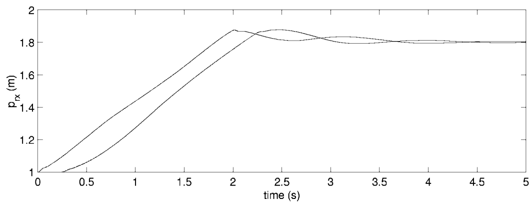

Figure 4: Free space: master (solid) and slave (dashed) along x direction.

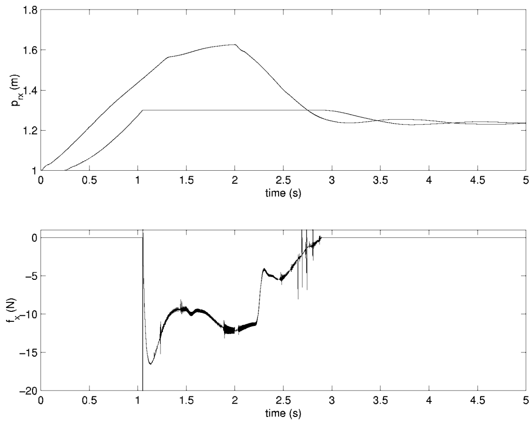

Figure 5: Interaction with an obstacle ($p_x = 1.3$): master (solid) and slave (dashed) along x direction and force applied to the environment at the slave side.

Such situations are typical in telemanipulation and are very useful to test: 1) trajectory tracking capabilities at the slave side; 2) force feedback at the master side in order to correctly perceive the remote environment. The simulations have been carried out with a constant time delay of $T = 0.2\ s$.

A first experiment was to apply a constant force $F_x = 10\ N$

along the x direction for 2 s, with and without obstacle at the remote side.

Figg. 4–5 show the results in the two cases of free space and with an obstacle. As one can appreciate in Fig. 4, considering the time-delay the tracking capability in free space of the slave manipulator is satisfying. When an obstacle is present at the remote side, Fig. 5, the master manipulator obviously initially passes the slave position. Then, it stops in a configuration that depends on the force applied by the operator and on the compliance of the springs and finally, when the operator does not apply any force, there is a convergence on a symmetric configuration of the two devices.

Other two specific tasks have been studied, considering both linear and rotational displacements:

1) screwing a bolt in a fixed position (p_{rx}, p_{ry} fixed; $p_{r\theta}$ varying)

2) turning a grip handle along a circular path (constraint on $p_{rx}, p_{ry}, p_{r\theta}$)

Fig. 6 shows the results obtained in these two tasks. In the first case, the operator applies a constant torque $M_\theta = 10\ Nm$ for 2 s. The master end effector has a limited displacement along the x and y directions, during screwing, due to transmission delays and manipulator controller. In the second task, the operator imposes a circular trajectory (with equation $(x-1)^2+y^2 = 0.3^2$) in the counter-clockwise direction and perceives correct orientation from the grip handle at the slave during the path.

5 Conclusion and Future Work

A control scheme for bilateral teleoperation systems based on passivity concepts has been presented and discussed. For this purpose, a proper redefinition of an IPC controller has been introduced, considering for the specific problem both a two-port interaction (robot and communication line) and an extension to a multi-dimensional case (linear and rotational displacements).

Simulations on two 3-dof planar manipulators show good results in a practical example, both in terms of tracking of a desired trajectory and rendering interactions with environment.

Future work will deal with the problem of position drift between master and slave, mainly due to varying time delays, see [14, 21] as possible approaches to the problem. Other activity will be devoted to the experimental evaluation of the proposed control scheme on real laboratory setups.

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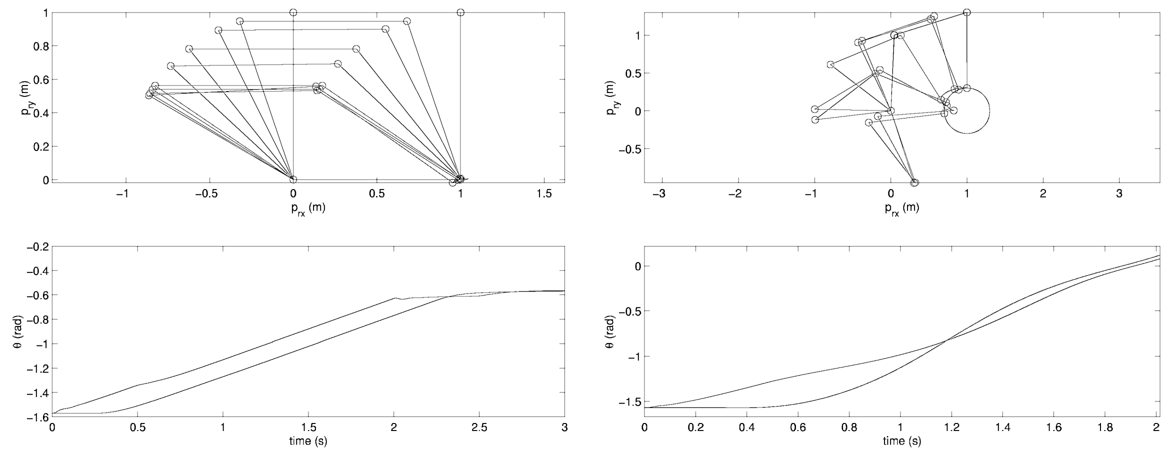

Figure 6: [Left] Screwing a bolt ($P_x = 1$, $P_y = 0$): master (solid) and slave (dashed) motion and end effector orientation P_θ. [Right] Turning a grip handle ($(x-1)^2 + y^2 = 0.3^2$, with the last link perpendicular to the trajectory): master and slave motion and orientation.

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