Optimized power modulation in wave based bilateral teleoperation

Federica Ferraguti, Marcello Bonfè, Cesare Fantuzzi and Cristian Secchi

***Abstract*—A common approach for stabilizing the delayed communication channel in a bilateral teleoperation architecture is using wave variables to make the exchange of information equivalent to a passive physical dynamics. However, such a dynamics is felt by the user and it affects the transparency of the system. In this paper, we exploit the wave variables for storing the energy exchanged between master and slave, but we shape the incoming power for reproducing a desired, transparent behavior. First, we propose a passivity preserving modulation of the incoming power, then we achieve possibly scaled desired forces and velocities. Finally, we formulate an optimization problem for computing the best values of forces and velocities to be implemented. A validation of the proposed architecture and the comparison of its performances with respect to the standard wave-based approach are provided.**

***Index Terms*—Telerobotics, teleoperation, transparency.**

I. Introduction

Bilateral teleoperation is a key research topic in robotics. After more than 50 years of history, it continues to be a fertile ground for theoretical exploration and application. A bilateral teleoperation system is made up of a user that interacts with two robots, the (local) master and the (remote) slave, interconnected by means of a bilateral control architecture. The motion of the master is sent to the slave and the slave replicates it. Conversely, the force existing between the slave and the remote environment is sent back to the master and felt by the user. The implementation of the desired coupling allows to achieve a transparent bilateral teleoperation system [1], which provides the human operator with the feeling of being directly operating on the remote environment. Master and slave exchange information over a communication channel, which is usually characterized by a non negligible delay. Because of their destabilizing effects, the time delay in the communication channel and the possibility for the slave to interact with a poorly known environment have been major problems for the implementation of a bilateral teleoperation architecture [2]. Ideally, perfect transparency and task performance should be satisfied simultaneously without affecting the stability of the system. Stabilization of the interaction of the slave with a poorly known environment is typically performed by using impedance control, while scattering/wave variables, introduced in [3], [4], have been used for passifying the communication channel independently of the delay. In this way, passive impedance controlled robots can be interconnected with a passive communication channel and, since the interconnection of passive systems is still passive [5], the overall teleoperation system is passive and, therefore, characterized by a stable behavior both in case of free motion and in case of interaction with unknown environments and in presence of the communication delay. Wave variables are almost a standard for stabilizing the delayed communication in bilateral teleoperation and they are still widely used (see e.g. [6], [7], [8], [9]). The success of wave variables is due to the simplicity of their implementation [4] and to the effectiveness in stabilizing the communication between local and remote sides even in case of variable time delays and packet loss [10]. The main idea behind the use of wave variables in teleoperation is to replicate physical phenomena such as wave propagation, which are characterized by a stable dynamics. Thus, power waves, a combination of force and velocity, rather than power variables, i.e. force and velocity, are transmitted. In this way, the communication channel stores the energy contained in the waves traveling from master to slave and viceversa and, consequently, it becomes a passive and stable energy storing element [4], [11]. Nevertheless, wave-based communication channels have a negative effect on the transparency of the overall teleoperation system, due to the fact that the communication channel is physically equivalent to a distributed mass-spring system. This drastically modifies the dynamic coupling between master and slave implemented, e.g., by means of impedance controllers [12]. Thus, such a physical embodiment of the wave-based channel has the advantage of making the exchange of information equivalent to a physical dynamics and, therefore, passive and stable. Nevertheless, such a physical dynamics is felt by the user, it influences the motion of the slave in an unplanned (and, usually, undesired) way and, consequently, it negatively affects the transparency of the teleoperation system. Extensions of the wave-based communication have then been proposed to solve this problem [13]. More recently, different methods to couple master and slave were also introduced, with the aim to achieve stability, flexibility and transparency. These approaches disembody the passivity of the communication channel by a particular dynamics. In particular, in [14] the concept of time domain passivity network (TDPN) is exploited for modeling standard teleoperation architectures. The delayed exchange of information is passified by using the PO/PC architecture [15], namely by activating a Passivity Controller (PC) only when the exchange of variables produces some energy that is observed by the Passivity Observer (PO). In [16] a neural network-based four-channel wave-based time domain passivity approach is

F. Ferraguti, C. Fantuzzi and C. Secchi are with the Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Italy. E-mail: {name.surname}@unimore.it

M. Bonfè is with the Department of Engineering, University of Ferrara, Italy. E-mail: marcello.bonfe@unife.it

proposed for a teleoperation system with time-varying delays. More recently, these approaches have been used and extended, e.g., in [17], [18]. In [19] the passive set-point modulation (PSPM) is exploited for the implementation of a position-position architecture over a delayed communication channel. At each side of the teleoperation system an energy reservoir stores the energy dissipated by the system and the position setpoint is scaled in such a way that the energy introduced is lower than the energy stored in the reservoir. In [20] a two layer architecture is proposed. In the passivity layer, a master energy tank and a slave energy tank store the energy that can be exploited for implementing any dynamic behavior without breaking the passivity constraint. In the transparency layer such an energy is exploited for implementing a desired transparent behavior. Energy tanks have also been recently successfully applied to implement variable impedance and manual/teleoperation transition in surgical teleoperation [21], multi-slave teleoperation [22] and hybrid force/impedance control [23]. Then, the two-layer approach has been recently extended to multi-master-multi-slave teleoperation [24]. Exhaustive reviews of the literature on the control methods for bilateral teleoperation systems can be found in [25], [26], [27]. While the recent approaches are more efficient in terms of transparency than the approach based on wave variables, since they don't introduce unwanted dynamics, the associated architectures are more complex to be implemented and they require tuning of several parameters in an empirical way.

In this paper we aim at blending the flexibility and the efficiency of the new methodologies with the simplicity of wave-based control in order to achieve a simple, passive and transparent bilateral teleoperation architecture. The main idea is to exploit the communication channel as an energy storing element and to control the way energy is extracted through the waves. Using a time-varying scaling matrix, it is possible to optimally shape the way the power in the wave is exploited in order to maximize the transparency of the teleoperation system while preserving its passivity. This work is an extension of [28] and [29]. In this paper, an extended theoretical and mathematical presentation is provided and the optimized energy modulation strategy proposed in [29] is combined with [28] and allows to cope with different directions of motion. Furthermore, the paper contains a detailed description of the experimental validation of the proposed transparency-oriented teleoperation scheme, highlighting its benefits in comparison with the standard wave-based teleoperation architecture. The wave-based method has been chosen as a reference for the comparison because it is also the one, among many others proposed in the literature, that is mostly comparable to our proposal in terms of conceptual simplicity and consequently limited computational burden required by its implementation. Therefore, the contributions of the paper are the following:

- The extended and detailed presentation of a transparency-oriented teleoperation architecture, inspired by the wave-based approach, embedding an optimization strategy that allows to fully exploit the energy stored by the communication channel for reproducing the desired behaviors at both master and slave side. The optimization strategy is also used to cope with different directions of motion.
- A combined theory between the component-wise modulation strategy proposed in [28] and the optimized modulation strategy presented in [29], with an extensive experimental evaluation of the performances of the novel strategy as compared to the previous.
- The practical application of the proposed architecture on a teleoperated peg insertion task, which is a case of study that involves simultaneous motions and contacts on multiple DOFs (i.e. translations and rotations). Evidence of significant improvements of the proposed strategy with respect to the standard wave-based teleoperation scheme is provided. The improvements are evaluated in terms of haptic feedback quality and motion tracking performance.

II. Background on Wave Variables

This section provides some background on scattering/wave-based teleoperation in order to introduce the main elements that will be exploited throughout the paper. In order to focus on the transmission line, we will consider the wave-based bilateral teleoperation architecture proposed in [12] and we will adopt the scattering variables formalism for the power waves proposed in [11]. Moreover, we will consider a constant communication delay. However, the results can be easily extended to time-varying delays following the approach proposed in [10]. Furthermore, all the results that will be developed in the paper can be easily extended to other wave-based teleoperation architectures and to other formalisms for denoting the waves. For details, the reader is addressed to [5].

The standard wave-based architecture is represented in Fig. 1. Master and slave are gravity compensated $n-$DOFs robots. In order to control and stabilize the interaction with a possibly unknown environment, the slave is connected to a passive impedance controller (e.g. a simple PD). The exchange of information between master and slave happens through the wave-based communication channel, which is characterized by a non negligible delay. The master sends the desired velocity to the impedance controller which uses it as a setpoint for moving the robot. The controller at the slave side transmits to the master the force applied to the robot, in order to provide the user with a force feedback. Formally, master and slave robots can be modeled as Euler-Lagrange systems:

$$\begin{aligned} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + D_m\dot{x}_m = F_h + F_m \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s + D_s\dot{x}_s = F_e + F_c \end{aligned} \tag{1}$$

where x_i is the pose of the end-effector, $M_i(x_i) > 0$ is the inertia matrix, $C(x_i, \dot{x}_i)$ is the matrix encoding the Coriolis/centrifugal forces and $D_i > 0$ is the dissipation matrix, where the subscript $i = \{m, s\}$ indicates the master and the slave respectively. F_h and F_e are the forces applied by the human and by the environment on the robots. F_c is the force applied by the controller to the slave and F_m is the force coming from the communication channel and applied to the master[1]. Here and in the following, in order to simplify the notation, sometimes we will not explicitly indicate the time

[1] With a slight abuse of notation, in the following we will call force what is actually a wrench and velocity what is actually a twist.

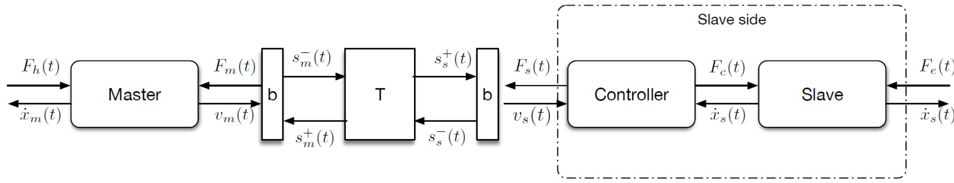


Fig. 1. Standard wave-based architecture.

dependency. The master can exchange energy with the operator and with the slave side through the power ports $(F_h, \dot{x}_m)$ and (F_m, v_m), where $v_m = \dot{x}_m$, respectively. Both ports have an admittance causality (force in/velocity out). As well known [5], a mechanical system is passive with the following balance:

$$\dot{H}_m(t) \leq (F_h^T + F_m^T) v_m \tag{2}$$

where $H_m(t) = \frac{1}{2}\dot{x}_m^T M_m(x_m)\dot{x}_m$ is the kinetic energy of the master. The slave can interact with the master through the controller. Since both the robot and the controller (e.g. a PD) are passive and since the interconnection of two passive systems is passive (see e.g. [5]), then the slave plus controller aggregate at the slave side is a passive system that can exchange energy with the environment and with the master side by means of the power ports $(F_e, \dot{x}_s)$, with an admittance causality, and (F_s, v_s), with an impedance causality (velocity in/force out), respectively. Since the slave side is passive, the following balance holds:

$$\dot{H}_s(t) \leq F_e^T \dot{x}_s + F_s^T v_s \tag{3}$$

where $H_s(t) = \frac{1}{2}\dot{x}_s^T M_m(x_s)\dot{x}_s + H_{cont}(t)$ is given by the sum of the kinetic energy of the slave robot and of the lower bounded energy function of the passive controller $H_{cont}(t)$.

The passivation of the communication channel is based on the following power decomposition, where the power flowing through a power port is decomposed into an incoming power wave and an outgoing power wave:

$$F_i^T(t)v_i(t) = \frac{1}{2}\|s_i^+(t)\|^2 - \frac{1}{2}\|s_i^-(t)\|^2 \quad i = \{m, s\} \tag{4}$$

where

$$\begin{cases} s_i^+(t) = \frac{R^{-1}}{\sqrt{2}}(F_i(t) + Bv_i(t)) \\ s_i^-(t) = \frac{R^{-1}}{\sqrt{2}}(F_i(t) - Bv_i(t)) \end{cases} \quad i = \{m, s\} \tag{5}$$

are the power waves associated to the power port (F_i, v_i), B is a symmetric positive definite wave impedance matrix and R is the symmetric square root of B (i.e. $B = RR$). Wave variables are transmitted along the delayed communication channel:

$$s_m^+(t) = s_s^-(t - T) \qquad s_s^+(t) = s_m^-(t - T) \tag{6}$$

where $T > 0$ is the communication delay. Transmitting the wave variables rather than the power variables makes the communication channel passive. Using (4), it results:

$$P_{ch}(t) = \frac{1}{2}\|s_m^-(t)\|^2 + \frac{1}{2}\|s_s^-(t)\|^2 - \frac{1}{2}\|s_m^+(t)\|^2 - \\ - \frac{1}{2}\|s_s^+(t)\|^2 = \dot{H}_{ch}(t) \tag{7}$$

where $P_{ch}(t)$ is the power flowing into the communication channel and, using (6), we have that

$$H_{ch}(t) = \int_{t-T}^{t} \left(\frac{1}{2}\|s_m^-(\tau)\|^2 + \frac{1}{2}\|s_s^-(\tau)\|^2 \right) d\tau \tag{8}$$

is a lower bounded energy function representing the energy stored into the channel. Thus, from (7) we can deduce that the communication channel is lossless and from (8) we can notice that the energy contained in the transmitted waves is stored in the channel until it is delivered. Since master and slave sides are passive and since the interconnection of passive systems is passive, the overall teleoperation system is passive with respect to the pair $((F_h^T F_e^T)^T, (\dot{x}_m^T \dot{x}_s^T)^T)$.

Master and slave sides receive an input a power variable (i.e. force/velocity) and, therefore, at each time step it is necessary to decode the information contained in the incoming power wave for computing the desired input and the outgoing power wave. Thus, for the master port with an admittance causality and the slave port with impedance causality we have that:

$$\begin{cases} F_m(t) = \sqrt{2}Rs_m^+(t) - Bv_m(t) \\ s_m^-(t) = s_m^+(t) - \sqrt{2}Rv_m(t) \end{cases} \tag{9}$$

where v_m is the output of the master side. Similarly, for the slave port, with an impedance causality, we have that:

$$\begin{cases} v_s(t) = \sqrt{2}R^{-1}s_s^+(t) - B^{-1}F_s(t) \\ s_s^-(t) = \sqrt{2}R^{-1}F_s(t) - s_s^+(t) \end{cases} \tag{10}$$

The communication protocol (6) encodes an energy exchange and it simply states that the power leaving one side is delivered to the other side. The coding/decoding procedures in (9) and (10) guarantee a passive coupling, but they implement a virtual distributed mass-spring system whose dynamics deteriorates the behavior of the teleoperation system. In other words, the way the power exchanged is exploited is responsible of the dynamic behavior that is implemented. A major problem of wave-based communication channels is the wave reflection [4] that can be eliminated by adding a matching damper, another unwanted dynamics that affects the behavior of the teleoperation system and that is felt by the user. Wave reflection is due to the fact that the standard wave-based communication channel mimics a physical phenomenon, namely physical wave transmission, and in this way all the effects of this phenomenon, as the wave reflection, are also replicated. As shown in the next sections, wave reflection is not detrimental for the proposed architecture since we exploit power waves only for transporting energy without mimicking any physical dynamics.

III. Transparent wave based teleoperation

One of the main insights in the two layer architecture [20] is the separation between passivity, i.e. the way energy flows in the system, and performance, i.e. the way energy flowing in the system is exploited. Loosely speaking a passive energy exchange is guaranteed and then the incoming energy is "shaped" in order to achieve the desired power variable making the system as transparent as possible while preserving passivity. In particular, in the two layer architecture two energy tanks are exploited for storing the energy at master and slave sides and the energy of the tanks is exploited for implementing the desired inputs on the robots.

In wave based teleoperation, the communication channel acts as a shared energy tank storing the energy exchanged in form of power waves and from/in which master and slave side can extract/inject energy. The main drawback in terms of transparency, as evident from (9) and (10), is that there is no control on how the received power is used for achieving the desired input for master and slave side. If the desired inputs change, the way the incoming energy is exploited for computing the real input remains the same. In this way the wave based communication channel provides the teleoperation system with a trade-off solution in terms of transparency. The main idea for increasing the transparency of a wave based teleoperation system is to introduce an extra degree of freedom that allows to catch the power wave coming from the communication channel and shape it in order to get the desired input to provide to the master and slave sides. The desired inputs can be computed on the basis of a (task dependent) transparency metric (see e.g. [30]), exploiting data collected from the user and the environment. In order to preserve a passive and stable behavior of the wave based architecture, we exploit a power preserving modulation for shaping the incoming power in a desired way. The power variables of master and slave side are modulated and then transformed using (5). The overall architecture is reported in Fig. 2. The modulation blocks implement the following interconnections:

$$\begin{cases} v_M(t) = W_m(t) v_m(t) \\ F_m(t) = W_m^T(t) F_M(t) \end{cases} \qquad \begin{cases} v_s(t) = W_s^T(t) v_S(t) \\ F_S(t) = W_s(t) F_s(t) \end{cases} \tag{11}$$

where $W_m(t), W_s(t) \in \mathbb{R}^{n\times n}$ are time varying matrix gains that can be used for shaping the incoming wave in order to obtain the desired (i.e. transparent) inputs for master and slave sides without violating the passivity of the overall teleoperation system. Indeed, the passivity of the teleoperation system with respect to the pair $((F_h^T, F_e^T)^T, (\dot{x}_m^T, \dot{x}_s^T))$ can be easily proven as follows. Summing (2) and (3) we obtain

$$\dot{H}_m(t) + \dot{H}_s(t) \leq F_m^T v_m + F_s^T v_s + F_h^T \dot{x}_m + F_e^T \dot{x}_s \tag{12}$$

The power contained in the wave variables is stored in the communication channel and, similarly to (7), we have that:

$$\tfrac{1}{2}\|s_M^-(t)\|^2 + \tfrac{1}{2}\|s_S^-(t)\|^2 - \tfrac{1}{2}\|s_M^+(t)\|^2 - \tfrac{1}{2}\|s_S^+(t)\|^2 = \dot{H}_{CH}(t) \tag{13}$$

where

$$H_{CH}(t) = \int_{t-T}^{t} \frac{1}{2}\|s_M^-(\tau)\|^2 + \frac{1}{2}\|s_S^-(\tau)\|^2 d\tau \tag{14}$$

Using (4) with (13) we have that:

$$F_M^T v_M + F_S^T v_S = -\dot{H}_{CH}(t) \tag{15}$$

From (11) it follows that

$$\begin{aligned} F_M^T(t) v_M(t) &= F_M^T(t) W_m(t) v_m(t) = F_m^T(t) v_m(t) \\ F_S^T(t) v_S(t) &= F_s^T(t) W_s^T(t) v_S(t) = F_s^T(t) v_s(t) \end{aligned} \tag{16}$$

Thus, using (16) with (15) and considering (12) we can write:

$$\dot{H}_m(t) + \dot{H}_s(t) \leq -\dot{H}_{CH}(t) + F_h^T \dot{x}_m + F_e^T \dot{x}_s \tag{17}$$

Let $\mathcal{H}(t) = H_m(t) + H_s(t) + H_{CH}(t)$ be the lower bounded energy function that represents the total energy stored in the teleoperation system. From (17) we can write:

$$\dot{\mathcal{H}}(t) \leq F_h^T \dot{x}_m + F_e^T \dot{x}_s \tag{18}$$

which proves the passivity of the overall system.

The particular choice of the wave impedance in the power decomposition (5) has an effect on the dynamic behavior of the wave based communication channel and a proper choice of this parameter influences the behavior of the teleoperation system, as shown in [12]. Nevertheless, we are exploiting the communication channel only as a means for transporting and storing energy and, using the matrix gains $W_m(t)$ and $W_s(t)$, we aim at shaping the stored energy for achieving a desired behavior, completely overriding any natural dynamics of the communication channel. Since the wave based transmission line transports energy for any symmetric positive definite choice of the wave impedance matrix B, in order to keep the mathematical formulation as simple as possible, we choose the identity matrix (i.e. $B = I$) for the power decomposition implemented in Fig. 2.

IV. Optimizing the use of energy for tuning the modulation blocks

In this section we will present the strategy for optimizing the use of the power contained in the incoming wave in order to tune the gain matrices $W_m(t)$ and $W_s(t)$ for choosing the best force/velocity to implement at the master/slave side. Optimization allows to get rid of the conservatism that characterizes passivity-based architectures, as shown in e.g. [31].

A. Requirements on modulation blocks

The tuning strategy of a matrix gain depends on the kind of input that needs to be computed from the incoming power wave. Thus, in the following, we will consider both the cases of a power port with admittance causality (e.g. the master side in Fig. 2) and the case of a power port with impedance causality (e.g. the slave side in Fig. 2).

1) Admittance Causality: We treat the admittance case by referring to the master side in Fig. 2. Let $F_{m_d}(t)$ be the desired input force. From the definition of the power waves in (5), with $B = I$, and from (11) we have that:

$$\begin{pmatrix} F_m(t) \\ s_M^-(t) \end{pmatrix} = \begin{pmatrix} -W_m^T(t) W_m(t) & \sqrt{2} W_m^T(t) \\ -\sqrt{2} W_m(t) & I \end{pmatrix} \begin{pmatrix} v_m(t) \\ s_M^+(t) \end{pmatrix} \tag{19}$$

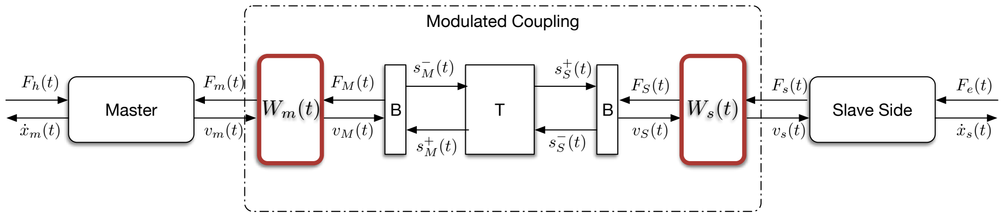


Fig. 2. The transparent wave-based architecture.

From which we can get:

$$F_m(t) = -W_m^T(t)W_m(t)v_m(t) + \sqrt{2}W_m^T(t)s_M^+(t) \quad (20)$$

$$s_M^-(t) = s_M^+(t) - \sqrt{2}W_m v_m(t) \quad (21)$$

Thus, by properly choosing $W_m(t)$, it is possible to change the input force F_m while preserving passivity. In particular, in order to apply the desired force $F_{m_d}(t)$ it is necessary to choose $W_m(t)$ such that:

$$W_m^T(t)W_m(t)v_m(t) - \sqrt{2}W_m^T(t)s_m^+(t) + F_{m_d}(t) = 0 \quad (22)$$

2) Impedance Causality: We treat the impedance case by referring to the slave side in 2. Let $v_{s_d}(t)$ be the desired input velocity. From the definition of the power waves in (5), with $B = I$, and from (11) we have that:

$$\begin{pmatrix} v_s(t) \\ s_S^-(t) \end{pmatrix} = \begin{pmatrix} -W_s^T(t)W_s(t) & \sqrt{2}W_s^T(t) \\ \sqrt{2}W_s(t) & -I \end{pmatrix} \begin{pmatrix} F_s(t) \\ s_S^+(t) \end{pmatrix} \quad (23)$$

From which we can get:

$$v_s(t) = -W_s^T(t)W_s(t)F_s(t) + \sqrt{2}W_s^T(t)s_S^+(t) \quad (24)$$

$$s_S^-(t) = -s_S^+(t) + \sqrt{2}W_s(t)F_s(t) \quad (25)$$

As for the admittance case, in order to provide the slave side with the desired velocity $v_{s_d}(t)$it is necessary to choose $W_s(t)$ such that:

$$W_s^T(t)W_s(t)F_s(t) - \sqrt{2}W_s^T(t)s_S^+(t) + v_{s_d}(t) = 0 \quad (26)$$

B. Component-Wise Modulation Strategy

A simple modulation strategy for finding the desired gain matrices would be to choose diagonal matrices $W_m(t) = diag(w_{m_1}(t), \dots, w_{m_n}(t))$ and $W_s(t) = diag(w_{s_1}(t), \dots, w_{s_n}(t))$ and to solve (22) and (26) component-wise. Considering the j-th component, (22) becomes the following second order equation:

$$v_j(t)w_j^2(t) - \sqrt{2}s_j^+(t)w_j(t) + F_{d_j}(t) = 0 \quad (27)$$

where the subscripts m and M have been omitted for ease of notation. If the master velocity is zero ($v_j(t) = 0$), (27) becomes

$$-\sqrt{2}s_j^+(t)w_j(t) + F_{d_j}(t) = 0 \quad (28)$$

The interaction with rigid environments is a common case in which it is necessary to provide a force to the master even if its velocity is zero. If some power is coming from the slave side ($s_j^+(t) \neq 0$) it is possible to reproduce the desired force by setting the modulation gain as:

$$w_j(t) = \frac{1}{\sqrt{2}}\frac{F_{d_j}(t)}{s_j^+(t)} \quad (29)$$

If no power is coming from the slave side ($s_j^+(t) = 0$), nothing can be shaped and therefore we set $w_j = 1$, reproducing in this way the standard wave based architecture. Notice, however, that this situation is very unlikely to happen since it means that we would like to implement a force on the master while we are not energetically interacting with the slave. If the master velocity is not equal to zero ($v_j \neq 0$) the gain w_j can be found by simply solving (27), which has a real solution only if its discriminant is non negative, namely if

$$\Delta E_j(t) = \frac{1}{2}(s_j^+(t))^2 - v_j(t)F_{d_j}(t) \geq 0 \quad (30)$$

From a physical point of view, this means that the desired force can be achieved only if the power requested for implementing $F_{d_j}(t)$ is not greater than the power contained in the incoming power wave. If the incoming power is sufficient for implementing the desired force, then $w_j(t)$ can be simply chosen as one of the real solutions of (27):

$$w_j(t) = \frac{\frac{1}{\sqrt{2}}s_j^+(t) \pm \sqrt{\Delta E_j(t)}}{v_j(t)} \quad (31)$$

If the difference between the available power and the requested power is negative ($\Delta E_j(t) < 0$), it is required to realize a scaled version of $F_{d_j}(t)$ in order to achieve the best approximation of $F_{d_j}(t)$ compatible with the passivity constraint. Thus, a scaling factor $\alpha_j(t) > 0$ is introduced to implement the force that is closest to the desired one:

$$\alpha_j(t) = \frac{\frac{1}{2}(s_j^+(t))^2}{F_{d_j}(t)v_j(t)} \quad (32)$$

Notice that, since $\Delta E_j(t) < 0$, then $v_j(t)F_{d_j}(t) > \frac{1}{2}(s_j^+)^2(t) \geq 0$ and therefore the definition of $\alpha_j(t)$ is always well posed. The scaled desired force $\alpha_j(t)F_{d_j}(t)$ is then computed by setting $w_j(t)$ as:

$$\frac{\frac{1}{\sqrt{2}}s_j^+(t) \pm \sqrt{\frac{1}{2}(s_j^+(t))^2 - \alpha_j(t)v_j(t)F_{d_j}(t)}}{v_j(t)} = \frac{s_j^+(t)}{\sqrt{2}v_j(t)} \quad (33)$$

which means that all the available power is exploited for implementing the scaled version of the desired force.

At the slave side, we can apply similar considerations to solve (26) component-wise for computing the components of the gain matrix $W_s(t)$.

While the presented simple approach, that we will call Component-Wise Modulation Strategy (CWMS) in the following, is also quite easy to implement, on the basis of the closed form solution of equations (22) and (26), it also implies that the desired force (velocity) at the master (slave) side on the j-th DOF is achieved only if there is enough power in the j-th component of the incoming power waves, that means:

$$\begin{aligned} &\tfrac{1}{2}(s^+_{M_j}(t))^2 - v_{m_j}(t)F_{m_{dj}}(t) \geq 0 \\ &\tfrac{1}{2}(s^+_{S_j}(t))^2 - F_{s_j}(t)v_{s_{dj}}(t) \geq 0 \end{aligned} \quad (34)$$

Otherwise, a scaled version of the desired force (velocity) values is produced, as already mentioned.

As evident from (21) and (25), the variable gains $W_m(t)$ and $W_s(t)$ influence also the computation of the power wave to be sent through the communication channel. The amount of power contained in the incoming wave and exploited for implementing the desired input affects the amount of power contained in the outgoing wave. Consider, for example, the master side of the proposed architecture (similar considerations hold for the slave side). By properly tuning $W_m(t)$, $F_m(t) = F_{m_d}(t)$. Thus, we have that:

$$F_m^T v_m = F_{m_d}^T v_m = F_M^T v_M = \frac{1}{2}\|s^+_M(t)\|^2 - \frac{1}{2}\|s^-_M(t)\|^2 \quad (35)$$

and, consequently

$$\frac{1}{2}\|s^-_M(t)\|^2 = \frac{1}{2}\|s^+_M(t)\|^2 - F_{m_d}^T v_m \quad (36)$$

Thus, if some power is necessary for implementing F_{m_d}, i.e. if $F_{m_d}^T v_m > 0$, the power of the outgoing wave is lower than the one of the incoming wave. On the other hand, if the desired force is dissipative, i.e. $F_{m_d}^T v_m \leq 0$, then the power of the outgoing wave is greater than the one of the incoming wave. In other words, the communication channel stores the energy dissipated through the port (F_m, v_m), similarly to what an energy tank does [20]. Implementing a dissipative behavior at the master side is a way of pumping energy to the slave side and vice-versa.

It is worth noting that, unlike in standard wave based communication channel, in the proposed architecture wave reflection is not detrimental: if some of the power of the incoming wave is not used, it is not dissipated through a matching damper as in [4], but it is sent back for being re-used.

C. Optimizing the use of energy

In a one dimensional case, it is possible to univocally compute the (scaled) value of the force/velocity to implement in such a way that the power flowing in to the master/slave slide is at most equal to the power contained in the incoming wave. This univocity is due to the fact that the available power and the force/velocity to be computed have the same dimension. In a multidimensional case, for a given power budget, several values of force/velocities can be computed. A possible way to choose a solution is to treat each dimension separately. Nevertheless, this introduces a strong conservatism. In fact, it can happen that, even if the incoming wave contains enough power for implementing the desired force/velocity, the power in some directions is not sufficient for implementing the desired force/velocity in that direction. This would lead to an unnecessary scaling of the force/velocity provided to the master/slave side and consequently to a degradation of the transparency.

Since the goal of the tuning of the modulation blocks is to choose the best force/velocity to be implemented at the master/slave side while using at most the power contained in the incoming wave variable, then it can be formulated as an optimization problem. Therefore, in the following we will refer to this solution as the Optimized Modulation Strategy (OMS).

Indeed, consider the master side and let

$$F_{m_d}(t) = \phi_m(F_e(t-T), v_m(t)) \in \mathbb{R}^n \quad (37)$$

be the desired force to implement on the master. The function ϕ_m represents a generic transparency function that depends on the contact force received by the slave side $F_e(t-T)$ and on the current master velocity $v_m(t)$.

At any time $t > 0$ we aim at computing $F_m(t)$ in such a way that the implemented force is as close as possible to the desired one while using at most the power contained in the incoming wave variable. In other words, we aim at solving the following optimization problem:

$$\begin{aligned} &\text{minimize} && \|F_m(t) - F_{m_d}(t)\|^2 \\ &\text{subject to} && F_m^T(t)v_m(t) \leq \frac{1}{2}\|s^+_M(t)\|^2 \end{aligned} \quad (38)$$

where $F_m(t)$ is the variable that has to be optimized and the constraint limits the power to be bounded by the incoming power. Consider now the slave side and let

$$v_{s_d}(t) = \phi_s(v_m(t-T), F_s(t)) \in \mathbb{R}^n \quad (39)$$

be the desired velocity to implement on the slave. The function ϕ_s represents a generic transparency metric that depends on the velocity received by the master side $v_m(t-T)$ and on the current slave force $F_s(t)$. ϕ_s could also be designed to include a position drift compensation as in [13].

At the slave side, at any time $t > 0$ the goal is to design $v_s(t)$ in such a way that the implemented velocity is as close as possible to the desired one while using at most the power incoming from the communication channel. In other words, at the slave side we aim at solving the following optimization problem:

$$\begin{aligned} &\text{minimize} && \|v_s(t) - v_{s_d}(t)\|^2 \\ &\text{subject to} && v_s^T(t)F_s(t) \leq \frac{1}{2}\|s^+_S(t)\|^2 \end{aligned} \quad (40)$$

where $v_s(t)$ is the variable that has to be optimized. In order to formulate (38) in the standard optimization formalism, we set for the master side $F_m(t) =: x = (x_1 \dots x_n)^T$, $F_{m_d}(t) =: a = (a_1 \dots a_n)^T$, $v_m(t) =: b = (b_1 \dots b_n)^T$ and $\frac{1}{2}\|s^+_M(t)\|^2 =: \sigma$. Similarly, to formulate (40) in the standard optimization form, we just need to set $x := v_s(t)$, $a := v_{s_d}(t)$, $b := F_s(t)$ and $\sigma := \frac{1}{2}\|s^+_S(t)\|^2$. Thus, both (38) and (40) can be formalized as quadratic optimization problems with a linear constraint:

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^{n} \left(x_i^2 - 2a_i x_i + a_i^2\right) \\ \text{subject to} \quad & \sum_{i=1}^{n} b_i x_i - \sigma \leq 0 \end{aligned} \tag{41}$$

The problem (41) can be solved using standard optimization techniques but, since it has to be solved in real time, we will also leverage on physical considerations for finding a solution in a fast and efficient way. First of all we check if it is possible to implement the desired value and this can be done with a very simple and fast computation. The linear constraint in (41) is the passivity constraint. If the desired force/velocity requires a power content lower than the one contained in the incoming wave, then it can be safely implemented. Formally we need to check if:

$$\sum_{i=1}^{n} b_i a_i - \sigma \leq 0 \tag{42}$$

If this is true, then $x = a$. If the constraint is not satisfied by the desired value, then we need to solve the constrained optimization problem. To this aim, we exploit the Lagrange multipliers methodology [32]. Thus, we first build the following augmented functional, where $\lambda \geq 0$:

$$J_A = \sum_{i=1}^{n} \left(x_i^2 - 2a_i x_i + a_i^2\right) + \lambda \left(\sum_{i=1}^{n} b_i x_i - \sigma \right) \tag{43}$$

which encodes both the function to be minimized and the constraint. The Lagrange multiplier λ serves the purpose of modifying (augmenting) the objective function from one quadratic to another quadratic so that the minimum of the modified quadratic satisfies the constraint.
The optimal solution (primal and dual) is $(x^\star, \lambda^\star)$, where $x^\star$ is the solution of (41), such that

$$\begin{pmatrix} \frac{\partial J_A}{\partial x} & \frac{\partial J_A}{\partial \lambda} \end{pmatrix}^T = 0 \tag{44}$$

which implies:

$$\underbrace{\begin{pmatrix} 2I_n & b \\ b^T & 0 \end{pmatrix}}_{M} \begin{pmatrix} x^\star \\ \lambda^\star \end{pmatrix} = \begin{pmatrix} 2a \\ \sigma \end{pmatrix} \tag{45}$$

By using the invertibility formula for block matrices, the inverse of the matrix M can be easily computed in closed form and it is easy to verify that M is always invertible if and only if $b \neq 0$. Notice that if $b = 0$, then (42) is always satisfied since $\sigma \geq 0$ and therefore the optimal solution is $x^\star = a$. If the optimization problem needs to be solved, it means that $b \neq 0$ and that, therefore, M is invertible. Thus:

$$\begin{pmatrix} x^\star \\ \lambda^\star \end{pmatrix} = M^{-1} \begin{pmatrix} 2a \\ \sigma \end{pmatrix} \tag{46}$$

where $x^\star$ is the closest force/velocity to the desired one.

Procedure MasterOptimization

Data: $F_{m_d}(t), s_M^+(t), v_m(t), W_m(t^-)$
$\sigma(t) = \frac{1}{2}\|s_M^+(t)\|^2$
$P_{req}(t) = \sum_{i=1}^{n} v_{m_j}(t) F_{m_{dj}}(t)$
if $P_{req}(t) - \sigma(t) \leq 0$ **then**
  $F_m^\star(t) = F_{m_d}(t)$
else
  $M = \begin{pmatrix} 2I_n & v_m(t) \\ v_m(t)^T & 0 \end{pmatrix}$
  $\begin{pmatrix} F_m^\star(t) \\ \lambda^\star(t) \end{pmatrix} = M^{-1} \begin{pmatrix} 2F_{m_d}(t) \\ \sigma(t) \end{pmatrix}$
$v_M(t) = W_m(t^-) v_m$
$F_M(t) = \sqrt{2} s_M^+(t) - v_M(t)$
for $j \leftarrow 1$ **to** n **do**
  if $F_{M_j}(t) \neq 0$ **then**
    $w_{m_j}(t) = F_{m_j}^\star(t) / F_{M_j}(t)$
  else
    $w_{m_j}(t) = 1$
$W_m(t) = \text{diag}(w_{m_1}(t), \ldots, w_{m_n}(t))$
$F_m(t) = W_m(t)^T F_M(t)$
$s_M^-(t) = s_M^+(t) - \sqrt{2} W_m(t) v_m(t)$

D. Tuning of the modulation blocks

The gain matrices $W_m(t)$ and $W_s(t)$ allow to shape the energy stored in the communication channel for achieving a desired behavior, overriding the natural dynamics of the communication channel. The solution (46) of the optimal problem can be used for tuning the modulation matrices $W_m(t)$ and $W_s(t)$.

Let $F_m^\star(t)$ and $v_s^\star(t)$ be the optimal solutions computed in (46) by solving the optimization problem (41). According to the wave variable approach, we can compute the variables $F_M(t)$ and $v_S(t)$ using (9) and (10). Then, by considering the modulation blocks (11) we can state the following relations between the optimal values to be implemented and the variables computed using the wave variables.

$$F_m^\star(t) = W_m^T(t) F_M(t) \qquad v_s^\star(t) = W_s^T(t) v_S(t) \tag{47}$$

Without loss of generality, we consider diagonal modulation matrices $W_m(t) = \text{diag}(w_{m_1}(t), \ldots, w_{m_n}(t))$ and $W_s(t) = \text{diag}(w_{s_1}(t), \ldots, w_{s_n}(t))$ since this is the simplest way for being able to act on every dimension. Each component on the diagonal is computed as:

$$w_{m_j}(t) = \frac{F_{m_j}^\star(t)}{F_{M_j}(t)} \qquad w_{s_j}(t) = \frac{v_{s_j}^\star(t)}{v_{S_j}(t)} \tag{48}$$

if $F_{M_j}(t) = 0$ or $v_{S_j}(t) = 0$, we set $w_{m_j}(t)$ ($w_{s_j}(t)$) to a constant value, reproducing passive wave based teleoperation. Then, from the definition of power waves, the wave variables $s_M^-(t)$ and $s_S^-(t)$ that have to be transmitted can be computed according to[2] (21) and (25). In the following we will provide a procedure for computing the gains $w_m(t)$ and $w_s(t)$ starting from the optimal values in order to optimize the wave-based teleoperation architecture. The optimization algorithm for the master side is reported in Alg. MasterOptimization.

Besides the desired force input $F_{m_d}(t)$, the incoming power wave that can be exploited $s_M^+(t)$, the velocity output of

[2] As shown in Sec. IV-A, in the proposed approach wave reflection is not a problem and, therefore, no countermeasure for preventing it must be taken.

the system $v_m(t)$ and the previous gain matrix $W_m(t^-)$ are required. Then, the total power incoming and the power requested to implement the desired force are computed in Lines 1 and 2. The first step in the optimization procedure is to check if the passivity constraint (42) is satisfied (Line 3). If it is, then the desired force $F_{m_d}(t)$ can be passively applied to the master device (Line 4). If the constraint is not satisfied, then the incoming power is not enough for implementing the desired force and the optimization problem has to be solved in order to find the closest force to the desired one. Following the procedure described in Sec. IV-C, the matrix M is computed according to (45) (Line 5) and the solution of the optimization problem is found from (46) (Line 6). Then, the variables $v_M(t)$ and $F_M(t)$ are computed using the standard wave variable theory according to (11) (Line 7) and applying (9) at the scheme in Fig. 2 (Line 8). In order to avoid algebraic loops, the variable $v_M(t)$ is computed based on the previous gain matrix $W_m(t^-)$. Then, $F_M(t)$ is used for computing the gain matrix $W_m(t)$. Indeed, the modulation block implements the relation between the force implemented at the master side and the force provided by the wave variable approach. We would like to implement the optimal value of the force just computed, thus this relation is given by (47) and we can compute the components of the gain matrix $W_m(t)$ as described in Line 10. If $F_{M_j}(t) = 0$, then we set the corresponding value of $w_{m_j}(t)$ to a default value of 1 (Line 11) since the product of $w_{m_j}(t)F_{M_j}(t)$ would give 0 anyway. Finally, by using the gain matrix $W_m(t)$ we can compute the force to be implemented at the master side (Line 13) and the outgoing power wave (Line 14). Thanks to the resolution of the optimization problem, the force implemented is the closest to the desired one that satisfy the passivity constraint.

At the slave side, similar considerations can be done. The algorithm SlaveOptimization is very similar to Alg. MasterOptimization and its explanation follow verbatim the one reported for the master side, with the only differences that the desired velocity $v_{s_d}(t)$ plays the role of $F_{m_d}(t)$, the force at the slave side $F_s(t)$ plays the role of $v_m(t)$ and the data inputs $s_M^+(t)$ and $W_m(t^-)$ are substituted by $s_S^+(t)$ and $W_s(t^-)$, respectively.

Procedure SlaveOptimization

Data: $v_{s_d}(t), s_S^+(t), F_s(t), W_s(t^-)$

1 $\sigma(t) = \frac{1}{2}\|s_S^+(t)\|^2$

2 $P_{req}(t) = \sum_{i=1}^{n} F_{s_j}(t) v_{s_{dj}}(t)$

3 **if** $P_{req}(t) - \sigma(t) \leq 0$ **then**

4 $\quad v_s^\star(t) = v_{s_d}(t)$

else

5 $\quad M = \begin{pmatrix} 2I_n & F_s(t) \\ F_s(t)^T & 0 \end{pmatrix}$

6 $\quad \begin{pmatrix} v_s^\star(t) \\ \lambda^\star(t) \end{pmatrix} = M^{-1} \begin{pmatrix} 2v_{s_d}(t) \\ \sigma(t) \end{pmatrix}$

7 $F_S(t) = W_s(t^-) F_s$

8 $v_S(t) = \sqrt{2} s_S^+(t) - F_S(t)$

for $j \leftarrow 1$ **to** n **do**

9 $\quad$ **if** $v_{S_j}(t) \neq 0$ **then**

10 $\quad\quad w_{s_j}(t) = v_{s_j}^\star(t) / v_{S_j}(t)$

$\quad$ **else**

11 $\quad\quad w_{s_j}(t) = 1$

12 $W_s(t) = \mathrm{diag}(w_{s_1}(t), \ldots, w_{s_n}(t))$

13 $v_s(t) = W_s(t)^T v_S(t)$

14 $s_S^-(t) = s_S^+(t) - \sqrt{2} W_s(t) F_s(t)$

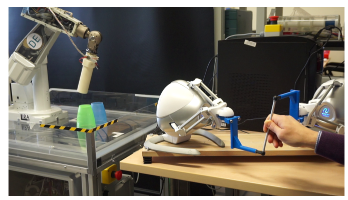


Fig. 3. Experimental setup for the peg-in-hole task.

V. Experiments

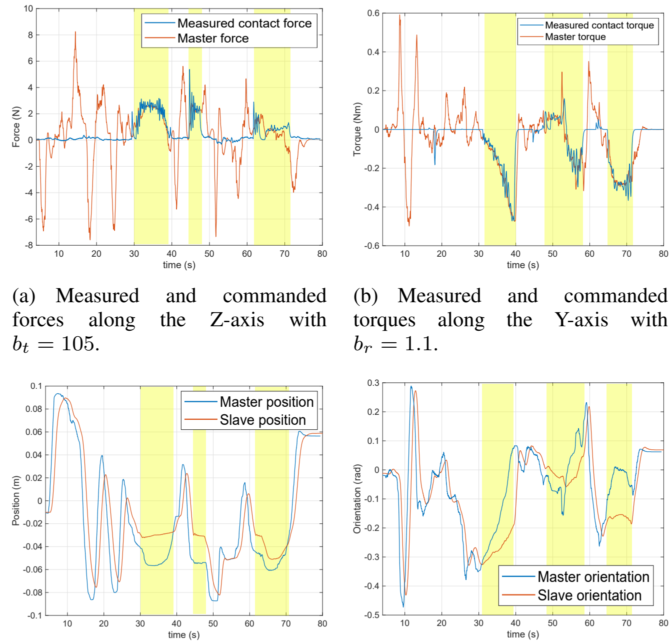
The proposed teleoperation architecture has been validated by means of experiments performed on a robotic system including as the slave, a Puma 260 6-DOF robot with a wrist-mounted 6-axis F/T sensor and as the master, a 5-DOF haptic system realized with a pair of Novint Falcons, coupled by a specifically designed assembly allowing the user to manipulate translation and orientation (i.e. pitch and roll angles) of a stylus, as described in [33] (see Fig. 3). The communication delay between master and slave has been emulated by means of FIFO buffering of exchanged data and the buffer size was set to obtain a value of $T = 300$ ms, which is comparable to an intercontinental transmission delay as remarked in [34].

The objective of the experiments described in this section is to emphasize the benefits of the proposed transparency-oriented architecture over standard wave-based teleoperation, especially considering robotic tasks involving simultaneous motions over multiple DOFs. For this purpose, a testbed has been prepared to execute the teleoperated insertion of a peg into a hole, as shown in the accompanying video. In particular, two plastic cups were fixed upside-down on the slave mounting table and the bottom of one of them was cut to allow the peg insertion. This task requires both translational and rotational motions, to achieve the proper alignment of the peg with the hole. Moreover, the user at the master side should properly receive force/torque feedback on all the DOFs involved by the task, which is technically feasible thanks to the features of the custom 5-DOF haptic device. Therefore, since the goal in this experiment is to directly reflect the force exerted by the environment, the transparency function in (37) is chosen as $\phi_m = F_e(t-T)$, while for the transparency function in (39) we chose $\phi_s = v_m(t-T)$. The following subsections present first the results obtained using the standard wave-based architecture shown in Fig. 1. Then, we introduce the results achieved with the proposed transparency-oriented scheme of Fig. 2, using either the Component-Wise Modulation Strategy (CWMS) described in Section IV-A or the Optimized Modulation Strategy (OMS) implemented by Algorithms MasterOptimization and SlaveOptimization.

A. Standard wave-based teleoperation behavior

Even though the wave-based teleoperation scheme is conceptually simple, its practical implementation and tuning require to address a number of relevant issues. Indeed, even starting from the seminal works [4] and [12], several extensions of the basic wave-based scheme have been proposed to include, for example, impedance matching or wave filtering. Such extensions are mainly designed to avoid wave reflections and to simplify wave impedance tuning. However, even in the most favorable condition (i.e. wave reflections perfectly compensated), the choice of the wave impedance plays a significative role on the dynamic behavior of the teleoperated system and requires a trade-off between speed of motion and the accuracy of the user feedback at master side. Moreover, impedance matching may be hard to achieve, with the solutions shown in [4], [12], especially when master and slave systems have quite dissimilar kinematics and/or dynamics, as is the case of our experimental setup. Therefore, in order to preserve the structural simplicity of the basic wave-based teleoperation approach, which is also the mainly desired feature of our proposed transparency-oriented scheme, we straightforwardly implemented the scheme of Fig. 1. To reduce wave reflections, the signals of (6) are processed by a first order low-pass filter, expressed in the Laplace domain as $(1+\tau s)^{-1}$ and tuned as suggested in [12]. In our setup, the haptic device at the master side is force-controlled, while the controller at the slave side (see Fig. 1) is represented by a PD controller that takes as input the velocity set-point computed by Eq. 10 and provides as output the control force to be applied to the slave. The slave robot, i.e. the Puma 260, is controlled by an admittance control which takes as input the control force plus the external force and computes the velocity to be applied by the robot low-level control [35]. The parameters of the admittance control (i.e. the virtual mass/inertia and the damping) were tuned to reduce the effects of abrupt transitions from free motion to contact with the stiff surface of the plastic cups. A virtual mass of 1 kg with a damping of 100 N/m/s was set for translational DOFs, while a virtual inertia of 0.01 kgm^2 with a damping of 1 Nm/rad/s was set for rotational DOFs. It is important to notice that this damping value has a relevant impact on wave impedance tuning. In the following, we assume that the wave impedance is specified as a diagonal matrix, with diagonal terms corresponding to translational DOFs equal to b_t and diagonal terms related to rotational DOFs equal to b_r (i.e. $B = diag\,[b_t, b_t, b_t, b_r, b_r, b_r]$). We performed several tests for tuning the terms of the wave impedance matrix. In particular, we implemented the following combinations: $b_t = 25$ - $b_r = 0.3$, $b_t = 75$ - $b_r = 0.8$ and $b_t = 105$ - $b_r = 1.1$, since it is suggested in [12] that the wave impedance should be higher than the master or slave dissipation.

The best tracking performance, without introducing too much resistance at the master side even when the slave is in free motion, were obtained by setting $b_t = 105$ and $b_r = 1.1$. Due to space limitations, we report only the results obtained with the best tuning. In particular, Figures 4(a) and 4(c) show, respectively, the forces and the positions along the Z-axis collected during the peg-in-hole test, while Figures 4(b) and 4(d) show, respectively, the torques and the angles around the Y-axis (i.e. the pitch orientation). We focus on the Z-axis translational and Y-axis rotational motions since they are particularly affected by contacts during peg insertion/extraction along the vertical direction. The yellow regions in Figures 4(c), 4(d) and in the remaining part of the section highlight the time intervals with contact conditions, significantly affecting master/slave tracking. It can be observed that forces and torques applied at the master side follow (with opposite sign) those computed by the PD controller at the slave side. Therefore, the master reproduces forces/torques due to contacts between the slave and the environment only when the robot is in static condition and the motion tracking error is mainly due to such contacts, otherwise the values due to motion tracking transients are rendered. The differences in the behavior of the teleoperation system, depending on the tuning of the wave impedance matrix, can be appreciated in the accompanying video.



(a) Measured and commanded forces along the Z-axis with $b_t = 105$.

(b) Measured and commanded torques along the Y-axis with $b_r = 1.1$.

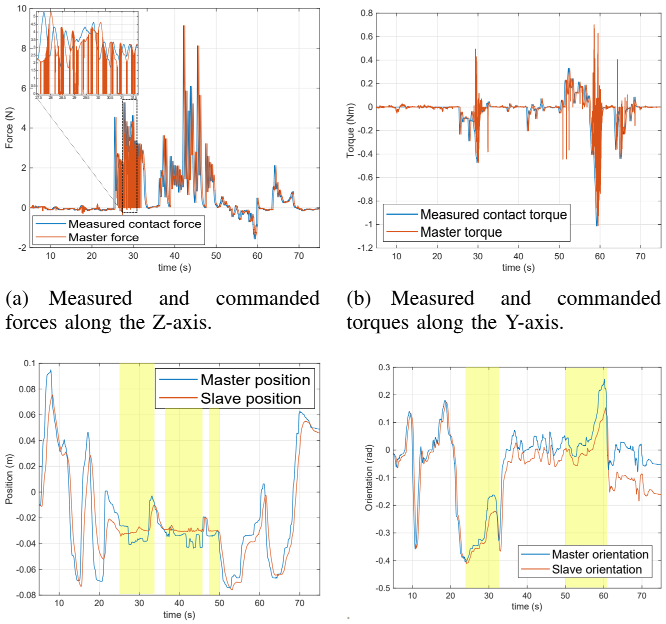
(c) Master and slave Z-axis position with $b_t = 105$.

(d) Master and slave pitch angle with $b_r = 1.1$.

Fig. 4. Results of the standard wave-based teleoperation with $b_t = 105$ and $b_r = 1.1$.

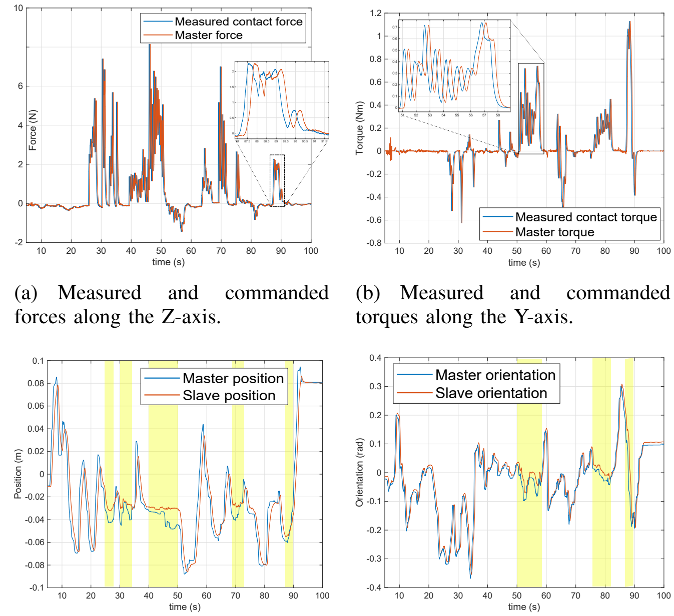
B. Transparent wave-based teleoperation behavior

The experiments on the peg-in-hole setup have been repeated applying the proposed transparency-oriented modification of the wave-based scheme. At first, the CWMS described in Section IV-A was used. It can be seen from Fig. 5(a) (forces along Z-axis), Fig. 5(c) (Z-axis positions), Fig. 5(b) (torques around Y-axis) and Fig. 5(d) (master and slave pitch angle) that the forces and torques rendered at the master side are consistent with those one actually measured by the F/T sensor mounted on the slave robot. Indeed, when the slave is in free motion, no haptic feedback is commanded to the master device, apart from a small viscous damping action that is artificially introduced to avoid a complete energetic disconnection between master and slave. Similarly, since the proposed approach is also able to passively reproduce the master velocity as the input to the slave robot velocity controller, the master/slave tracking performance are quite good.



(a) Measured and commanded forces along the Z-axis. (b) Measured and commanded torques along the Y-axis. (c) Master and slave Z-axis position. (d) Master and slave pitch angle.

Fig. 5. Results of the transparency-oriented architecture with CWMS.



(a) Measured and commanded forces along the Z-axis. (b) Measured and commanded torques along the Y-axis. (c) Master and slave Z-axis position. (d) Master and slave pitch angle.

Fig. 6. Results of the transparency-oriented architecture with OMS.

However, it is also important to note that using the CWMS it may happen, especially during contact conditions that do not allow slave motion along a particular direction, that the power available in the wave variables is not sufficient to implement the desired force along that direction. This situation is visible in small transients of Fig. 5(a), in which it is also emphasized, and Fig. 5(b). The modulation algorithms described in Section IV-C (i.e. OMS) are able to practically eliminate this issue. Thanks to the optimized distribution of the full power encoded by the wave variables, it is possible to exploit such a power on the DOFs in which it is mostly necessary (i.e. those requiring the application of a desired force/torque or the generation of a desired motion). As can be seen from Fig. 6(a) (forces along Z-axis), Fig. 6(c) (Z-axis positions), Fig. 6(b) (torques around Y-axis) and Fig. 6(d) (master and slave pitch angle), the measured contact forces/torques are accurately replicated at the master device, after a delay consistent with the emulated intercontinental communication. Finally, the master/slave position tracking is also pretty accurate, apart from the obvious mismatch during contacts with stiff surfaces. It is important to remark that the tracking and forces/torques rendering performances are obtained without the need of any particular tuning of control parameters, apart from those at the slave side (i.e. velocity PD regulator and admittance control).

VI. Conclusions

Controlling the robot in teleoperation brings several challenges, especially when a bilateral coupling is desired. In particular, unstable behaviors may arise when delays are present in the communication channel and while interacting with poorly known environments. Moreover, the dynamics of the controllers affect the force fed back to the user and they can prevent from implementing the desired feedback. As a consequence, the transparency and the performances of the system are affected. Wave variables are almost a standard for stabilizing the delayed communication channel. However, wave-based communication channels have a negative effect on the transparency of the overall teleoperation system. More recently, more flexible and transparent coupling between master and slave have been proposed (e.g. TDPN, PO/PC architecture, PSPM, two-layer approach) but the associated architectures are more complex to be implemented and they require tuning of several parameters. In this paper we blended the flexibility and efficiency of the new methodologies with the simplicity of the wave-based architectures. We proposed a passivity preserving modulation of the incoming power and we formulated an optimization problem for tuning the gain matrices. We presented an extensive validation of the proposed framework and we performed several experiments for comparing the proposed strategy with respect to the standard wave-based approach. Future works aim at reducing the conservatism due to the fact that in the proposed approach it is considered the power exchanged through wave variables. An even more efficient approach will be to consider the energy exchanged instead of considering the power.

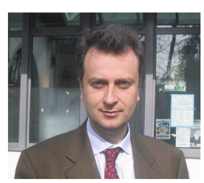
References

[1] D. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. on Robotics and Automation*, 1993.
[2] W. R. Ferrell, "Delayed force feedback," *IEEE Trans. on Human Factors Electronics*, vol. HFE-8, pp. 449–455, Oct. 1966.
[3] R. Anderson and M. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. on Automatic Control*, vol. 34, no. 5, pp. 494–501, 1989.
[4] G. Niemeyer and J. Slotine, "Stable adaptive teleoperation," *IEEE J. of Oceanic Engineering*, vol. 16, no. 1, pp. 152–162, 1991.
[5] C. Secchi, S. Stramigioli, and C. Fantuzzi, *Control of interactive robotic interfaces: a port-Hamiltonian approach*, ser. Springer Tracts in Advanced Robotics. Springer, 2007.

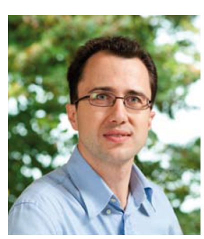
[6] P. Huang, P. Dai, Z. Lu, and Z. Liu, “Asymmetric wave variable compensation method in dual-master-dual-slave multilateral teleoperation system,” *Mechatronics*, vol. 49, pp. 1 – 10, 2018.
[7] D. Sun, F. Naghdy, and H. Du, “Wave-variable-based passivity control of four-channel nonlinear bilateral teleoperation system under time delays,” *IEEE/ASME Trans. on Mechatronics*, vol. PP, no. 99, 2015.
[8] J. Luo, C. Liu, N. Wang, and C. Yang, “A wave variable approach with multiple channel architecture for teleoperated system,” *IEEE Access*, vol. 7, pp. 143 912–143 920, 2019.
[9] J. Guo, C. Liu, and P. Poignet, “A scaled bilateral teleoperation system for robotic-assisted surgery with time delay,” *Journal of Intelligent and Robotic Systems*, vol. 95, no. 1, pp. 165–192, 2019.
[10] S. Stramigioli, C. Secchi, A. van der Schaft, and C. Fantuzzi, “Sampled data systems passivity and discrete port-hamiltonian systems,” *IEEE Trans. on Robotics*, vol. 21, no. 4, pp. 574–587, 2005.
[11] S. Stramigioli, A. van der Schaft, B. Maschke, and C. Melchiorri, “Geometric scattering in robotic telemanipulation,” *IEEE Trans. on Robotics and Automation*, vol. 18, no. 4, pp. 588–596, Aug 2002.
[12] G. Niemeyer and J.-J. Slotine, “Telemanipulation with time delays,” *Int. J. of Robotics Research*, vol. 23, no. 9, pp. 873–890, Sep 2004.
[13] C. Secchi, S. Stramigioli, and C. Fantuzzi, “Position drift compensation in port-hamiltonian based telemanipulation,” in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Beijing, China, 2006.
[14] J. Artigas, J.-H. Ryu, C. Preusche, and G. Hirzinger, “Network representation and passivity of delayed teleoperation systems,” in *Proc. of the IEEE/RSJ Int. Conf. onIntelligent Robots and Systems*, Sept 2011, pp. 177–183.
[15] B. Hannaford and J.-H. Ryu, “Time domain passivity control of haptic interfaces,” *IEEE Trans. on Robotics and Automation*, vol. 18, no. 1, pp. 1–10, February 2002.
[16] D. Sun, F. Naghdy, and H. Du, “Neural network-based passivity control of teleoperation system under time-varying delays,” *IEEE Transactions on Cybernetics*, vol. 47, no. 7, pp. 1666–1680, 2017.
[17] M. Panzirsch, J.-H. Ryu, and M. Ferre, “Reducing the conservatism of the time domain passivity approach through consideration of energy reflection in delayed coupled network systems,” *Mechatronics*, vol. 58, pp. 58 – 69, 2019.
[18] A. Coelho, H. Singh, T. Muskardin, R. Balachandran, and K. Kondak, “Smoother position-drift compensation for time domain passivity approach based teleoperation,” in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Oct 2018, pp. 5525–5532.
[19] D. Lee and K. Huang, “Passive-set-position-modulation framework for interactive robotic systems,” *IEEE Trans. on Robotics*, vol. 26, no. 2, pp. 354–369, April 2010.
[20] M. Franken, S. Stramigioli, S. Misra, C. Secchi, and A. Macchelli, “Bilateral telemanipulation with time delays: A two-layer approach combining passivity and transparency,” *IEEE Trans. on Robotics*, vol. 27, no. 4, pp. 741–756, Aug 2011.
[21] F. Ferraguti, N. Preda, A. Manurung, M. Bonfe, O. Lambercy, R. Gassert, R. Muradore, P. Fiorini, and C. Secchi, “An energy tank-based interactive control architecture for autonomous and teleoperated robotic surgery,” *IEEE Trans. on Robotics*, vol. 31, no. 5, pp. 1073–1088, 2015.
[22] P. Robuffo Giordano, A. Franchi, C. Secchi, and H. Buelthoff, “A passivity-based decentralized strategy for generalized connectivity maintenance,” *The Int. J. of Robotics Research*, vol. 32, no. 3, pp. 299–323, 2013.
[23] C. Schindlbeck and S. Haddadin, “Unified passivity-based cartesian force/impedance control for rigid and flexible joint robots via task-energy tanks,” in *Proc. of the IEEE Int. Conf. on Robotics and Automation*, May 2015, pp. 440–447.
[24] M. Minelli, F. Ferraguti, N. Piccinelli, R. Muradore, and C. Secchi, “An energy-shared two-layer approach for multi-master-multi-slave bilateral teleoperation system.” in *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Montreal, Canada, May 2019.
[25] P. M. Kebria, H. Abdi, M. M. Dalvand, A. Khosravi, and S. Nahavandi, “Control methods for internet-based teleoperation systems: A review,” *IEEE Trans. on Human-Machine Systems*, vol. 49, no. 1, pp. 32–46, 2019.
[26] P. Hokayem and M. Spong, “Bilateral teleoperation: An historical survey,” *Automatica*, vol. 42, no. 12, 2006.
[27] D. Sun, F. Naghdy, and H. Du, “Application of wave-variable control to bilateral teleoperation systems: A survey,” *Annual Reviews in Control*, vol. 38, no. 1, pp. 12 – 31, 2014.
[28] C. Secchi, F. Ferraguti, and C. Fantuzzi, “Catching the wave: a transparency oriented wave based teleoperation architecture,” in *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Stockholm, Sweden, May 2016.
[29] F. Ferraguti, C. Fantuzzi, and C. Secchi, “Optimizing the use of power in wave based bilateral teleoperation,” in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Daejon, Korea, Oct 2016.
[30] C. Secchi, S. Stramigioli, and C. Fantuzzi, “Transparency in port-hamiltonian-based telemanipulation,” *IEEE Trans. on Robotics*, vol. 24, no. 4, pp. 903–910, August 2008.
[31] M. De Stefano, R. Balachandran, and C. Secchi, “A passivity-based approach for simulating satellite dynamics with robots: Discrete-time integration and time-delay compensation,” *IEEE Trans. on Robotics*, pp. 1–15, 2019.
[32] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.
[33] G. Ateş, L. Brunetti, and M. Bonfè, “Improved usability of a low-cost 5-dof haptic device for robotic teleoperation,” in *ROMANSY 22 – Robot Design, Dynamics and Control*, V. Arakelian and P. Wenger, Eds. Springer International Publishing, 2019, pp. 213–221.
[34] M. Riedel, A. Franchi, P. Robuffo Giordano, H. H. Buelthoff, and H. Son, “Experiments on intercontinental haptic control of multiple uavs,” in *Proc. of the 12th Int. Conf. on Intelligent Autonomous Systems*, Jeju Island, korea, June 2012.
[35] F. Ferraguti, C. Talignani Landi, L. Sabattini, Bonfè, C. Fantuzzi, and C. Secchi, “A variable admittance control strategy for stable physical human–robot interaction,” *The Int. J. of Robotics Research*, 2019.

Federica Ferraguti received the M.Sc. degree in Industrial and Management Engineering and the Ph.D. in Industrial Innovation Engineering from the University of Modena and Reggio Emilia, Italy, in 2011 and 2015. She is currently an Assistant Professor at the University of Modena and Reggio Emilia. In 2017 she received the “Fabrizio Flacco Young Author Best Paper Award” from the IEEE Robotics and Automation Society – Italian Chapter. Her research deals with surgical robotics, telerobotics, control of robotic systems and human-robot physical interaction, collaborative robotics.

Marcello Bonfè received the M.Sc. degree in Electronic Engineering in 1998, and the Ph.D. in Information Engineering in 2003. He is Assistant Professor of Automatic Control at the University of Ferrara, Italy. His main research interests are: motion planning and control for robotics, modelling and control of mechatronic systems, fault detection and fault tolerant control.



Cesare Fantuzzi received the M.S. degree in Electrical Engineering and Ph.D. degree in System Engineering from the University of Bologna (Italy) in 1990 and 1995, respectively. Prof. Fantuzzi is a Full Professor of Automatic Control at University of Modena and Reggio Emilia. He has held positions as project leader in several applied research programs developed in cooperation with companies in the field of packaging machinery builder and manufacturing. His research interests are in the theory and application of discrete-event control for automatic machinery and in the modeling and control of Mechatronics system and robots.



Cristian Secchi graduated in Computer Science Engineering at the University of Bologna in 2000 and he received his Ph.D. in Information Engineering in 2004 from the University of Modena and Reggio Emilia, where he is currently Full Professor. His Ph.D. thesis has been selected as one of the three finalists of the 5th Georges Giralt AwardHe participated to the CROW project, selected as one of the finalists for the 2010 EUROP/EURON Technology Transfer AwardHis research deals with human-robot physical interaction, telerobotics, mobile robotics and surgical robotics.