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Catching the wave: a transparency oriented wave based teleoperation architecture

Cristian Secchi, Federica Ferraguti and Cesare Fantuzzi

Abstract— **Wave variables are a very popular approach for dealing with communication delay in bilateral teleoperation because of their effectiveness and of their simplicity. Nevertheless, the inherent dynamics of wave based communication channels is often deleterious for the transparency of the teleoperation system. Recently proposed architectures like TDPN, PSPM and two layers approach allow to achieve a high transparency at the price of a complex architecture, with some parameters to tune empirically. In this paper we propose a novel wave based architecture that blends the high performance that can be achieved by recently proposed architectures with the simplicity of wave based bilateral teleoperation.**

I. INTRODUCTION

The main objective of bilateral teleoperation is to establish a desired dynamic coupling between a local robot (the master) and a remote robot (the slave) exchanging information over a communication channel characterized by a non negligible delay. Such a coupling allows a human operator to transmit the motion of the master to the slave, to control the way the slave interacts with the environment and to provide a force feedback informative of the remote interaction to the human. In other words, the implementation of the desired coupling allows to achieve a *transparent* bilateral teleoperation system [1], [2], which provides the human operator with the feeling of being directly operating on the remote environment.

Because of their destabilizing effect, the communication delay and the possibility for the slave to interact with a poorly known environment have been major problems for the implementation of a bilateral teleoperation system since the early days of telerobotics [3]. In the last two decades, passivity theory and passivity based control have been successfully exploited for addressing these issues and for achieving a stable bilateral teleoperation system (see e.g. [4] for an exhaustive survey). In particular, impedance control has been and it is still extensively used for stabilizing the interaction of the slave with the, possibly unknown, remote environment. Scattering/wave variables, introduced in [5], [6], have been used for passifying the communication channel independently of the delay. In this way, it is possible to interconnect passive impedance controlled robots with a passive communication channel and, since the interconnection of passive systems is still passive [7], 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.

Since the early 90s, wave variables have become almost a standard for stabilizing the delayed communication in teleoperation and they are still widely used (see e.g. [8]). Such a success is due to two key factors: the simplicity of their implementation, they are just an algebraic manipulation of force and velocity [6], and their effectiveness in stabilizing the delayed communication between local and remote sides, also in case of variable delays and packets loss (see e.g. [9]).

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 are transmitted, 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 [6], [10]. 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 [11]. 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.

This problem has been partially addressed extending the wave based communication (see e.g. [12]). More recently, it has been recognized that the passivity of the communication channel can be disembodied by a particular physical dynamics and this allows to implement more flexible and transparent coupling between master and slave. In the Time Domain Passivity Network (TDPN) approach [13] the PO/PC architecture [14] is exploited for dissipating energy only when passivity is violated. In the passive set-point modulation (PSPM) [15] energy reservoirs are exploited for implementing an energy aware scaling in a position-position architecture. In [16] 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

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is exploited for implementing a desired transparent behavior. Energy tanks have also been recently successfully applied to the variable impedance and manual/teleoperation transition in surgical teleoperation [17] and to multi-slave teleoperation [18], [19] and for hybrid force/impedance control [20].

While these approaches are more efficient than the wave based architecture since they do not introduce unwanted dynamics that affect the transparency of the system, the associated control architecture is by far more complex to implement (e.g. the dynamics of the energy reservoirs/tanks has to be reproduced) and several parameters need to be tuned in an empirical way (e.g. upper and lower tresholds in energy tanks/reservoirs in [15], [16] and the way energy flows are split in [13]). The main intuition behind [16] is to implement a passive energy exchange and then to arbitrarily exploit the available energy for obtaining the desired behavior. In this paper we aim at exploiting this intuition for blending the flexibility and the efficiency of [16] with the simplicity of wave based architectures in order to achieve simple, passive and transparent bilateral teleoperation architecture. As in [6], we will exploit wave variables for storing the energy exchanged between master and slave but, as in [16], we will shape the power contained in the incoming wave for reproducing a desired, transparent behavior. This can be done by replacing the algebraic manipulation proposed in [6] for computing the inputs of master and slave from the incoming wave with another algebraic manipulation. This preserves the simplicity of the wave based architecture but it also takes into account the desired behavior to implement as in [16], rather than implementing just a passive but undesired physical coupling as in [6].

Thus, the contribution of this paper is a wave based bilateral teleoperation architecture which is as simple as the one proposed in [6] and that explicitly addresses transparency as in [16]. The proposed architecture does not require either complex structures or the empirical tuning of parameters for its implementation.

II. Wave based teleoperation

In this section we will briefly present the standard scattering/wave based teleoperation architecture in order to introduce the main elements that we will exploit for developing the new architecture proposed in this paper. For more information, the reader is addressed to [11], [7]. Many variants of wave-based bilateral teleoperation architectures have been proposed in the literature but here, in order to focus on the transmission line, we will consider the simplest one, proposed in [11]. Furthermore, we will adopt the scattering variables formalism, proposed in [10] for the power waves and we will consider a constant communication delay. 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.

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 master sends the desired velocity to the impedance controller which uses it as a setpoint for moving the robot. The slave side transmits through the controller the force applied to the robot to the master side in order to provide the user with a force feedback. The exchange of information happens through the wave based communication channel.

Formally, master and slave robots can be modeled as Euler-Lagrange system:

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

where x_i, $M_i(x_i) > 0$, $C(x_i,\dot{x}_i)$ and $D_i > 0$, with $i = \{m,s\}$, are the pose of the end-effector, the inertia matrix, the matrix encoding the Coriolis and the centrifugal forces and the dissipation matrix 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 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 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 (see e.g. [7]), a mechanical system is passive and, therefore, the following balance holds:

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

where $H_m(t) = \frac{1}{2}\dot{x}_m M_m(x_m)\dot{x}_m$ 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. [7]), then 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:

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

where $H_s(t) = \frac{1}{2}\dot{x}_s M_m(x_s)\dot{x}_s + H_{cont}(t)$ 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:

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

[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.

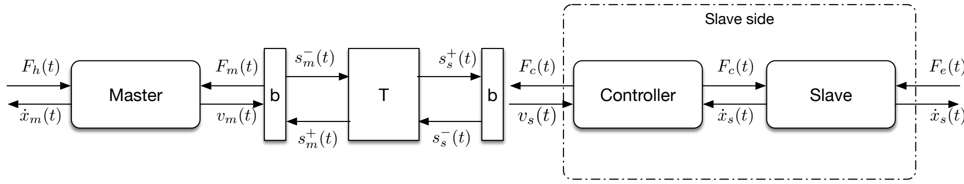


Fig. 1. Wave-based architecture

where

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

are the power waves associated to the power port (F_i, v_i) and $b \in \mathbb{R}^+$ is the wave impedance. Wave variables are transmitted along the delayed communication channel:

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

where $T > 0$ is the communication delay. Transmitting the wave variables rather than the power variables makes the communication channel passive. 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 as an input a power variable (i.e. force or 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:

$$\begin{cases} F_m(t) = \sqrt{2b}s_m^+(t) - bv_m(t) \\ s_m^-(t) = s_m^+(t) - \sqrt{2b}v_m(t) \end{cases} \quad \begin{cases} v_s(t) = \sqrt{\frac{2}{b}}s_s^+(t) - \frac{1}{b}F_s(t) \\ s_s^-(t) = \sqrt{\frac{2}{b}}F_s(t) - s_s^+(t) \end{cases} \tag{7}$$

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 (7) 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 [6] 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 is passive because it 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

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 (7), 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. [2]), exploiting data collected from the user and the environment. In order to preserve a passive and stable behavior of the wave based architecture, we will 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 proposed architecture is reported in Fig. 2.

The modulation blocks implement the following interconnections:

$$\begin{cases} v_M(t) = W_m(t)v_m(t) \\ F_m(t) = W_m^T(t)F_M(t) \end{cases} \quad \begin{cases} v_s(t) = W_s^T(t)v_S(t) \\ F_S(t) = W_s(t)F_s(t) \end{cases} \tag{8}$$

where $W_m(t), W_s(t) \in \mathbb{R}^{n\times n}$ are time varying matrix gains.

Proposition 1: The overall teleoperation system is passive with respect to the pair $((F_h^T, F_e^T)^T, (\dot{x}_m^T, \dot{x}_s^T))$

Proof: Summing (2) and (3) we obtain

$$\dot{H}_m(t) + \dot{H}_s(t) \le F_m^T v_m + F_s^T v_s + F_h^T \dot{x}_m + F_e^T \dot{x}_s \tag{9}$$

The power contained in the wave variables is stored in the communication channel and we have that [6], [7]:

$$\frac{1}{2}\|s_M^-(t)\|^2 + \frac{1}{2}\|s_S^-(t)\|^2 - \frac{1}{2}\|s_M^+(t)\|^2 - \frac{1}{2}\|s_S^+(t)\|^2 = \dot{H}_{CH}(t) \tag{10}$$

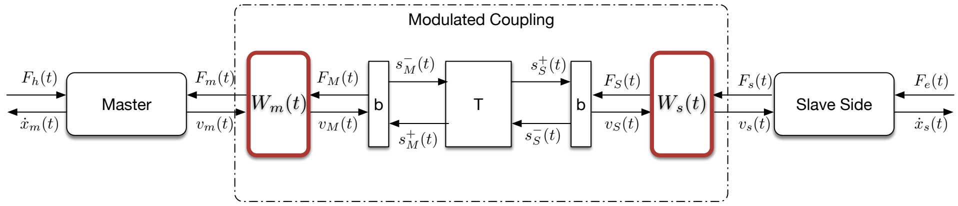


Fig. 2. The overall architecture

where

$$H_{CH}(t) = \int_{t-T}^{t} \frac{1}{2}\|s_M^-(\tau)\|^2 + \frac{1}{2}\|s_S^-(\tau)\|^2 d\tau \quad (11)$$

Using (4) with (10) we have that:

$$F_M^T v_M + F_S^T v_S = -\dot{H}_{CH}(t) \quad (12)$$

From (8) we have that

$$\begin{aligned} F_M^T(t)v_M(t) &= F_M^T(t)W_m(t)v_m(t) = F_m^T(t)v_m(t) \\ F_S^T(t)v_S(t) &= F_s^T(t)W_s^T(t)v_S(t) = F_s^T(t)v_s(t) \end{aligned} \quad (13)$$

Thus, using (13) with (12) and considering (9) we can write:

$$\dot{H}_m(t) + \dot{H}_s(t) \leq -\dot{H}_{CH}(t) + F_h^T\dot{x}_m + F_e^T\dot{x}_s \quad (14)$$

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 (14) we can write $\dot{\mathcal{H}}(t) \leq F_h^T\dot{x}_m + F_e^T\dot{x}_s$ which proves the passivity of the overall system and concludes the proof. ■

Thus, exploiting the time varying modulation strategy reported in (8), we have endowed a wave based communication strategy with extra control parameters, the gains $W_m(t)$ and $W_s(t)$, that can be used for shaping the incoming wave in order to obtain the desired inputs for master and slave sides without violating the passivity of the overall teleoperation system.

IV. Modulation Strategy

In this section we present a strategy for tuning the variable gains $W_m(t)$ and $W_s(t)$ in order to achieve the desired (i.e. transparent) inputs for master and slave sides. 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 [11]. 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 value $b > 0$ of the wave impedance, in order to keep the math as simple as possible, we choose $b = 1$ for the power decomposition implemented in Fig. 2.

Consider the master side in Fig. 2, where the incoming wave has to be exploited for computing a force input

Procedure Modulation

Data: $F_{d_j}(t), s_j^+(t), v_j(t)$
if $v_j(t) = 0$ **then**
    if $s_j^+(t) \neq 0$ **then**
        $w_j(t) = \frac{1}{\sqrt{2}}\frac{F_{d_j}(t)}{s_j^+(t)}$
    else
        $w_j(t) = 1$
else
    $\Delta E_j(t) = \frac{1}{2}(s_j^+(t))^2 - v_j(t)F_{d_j}(t)$
    if $\Delta E_j(t) \geq 0$ **then**
        $w_j(t) = \frac{\frac{1}{\sqrt{2}}s_j^+(t) \pm \sqrt{\Delta E_j(t)}}{v_j(t)}$
    else
        $\alpha_j(t) = \frac{\frac{1}{2}(s_j^+(t))^2}{F_{d_j}(t)v_j(t)}$
        $w_j(t) = \frac{s_j^+(t)}{\sqrt{2}v_j(t)}$

(admittance causality). Let $F_{m_d}(t)$ be the desired input force. From the definition of the power waves in (5), with $b = 1$, and from (8) we have that:

$$F_m(t) = -W_m^T(t)W_m(t)v_m(t) + \sqrt{2}W_m^T(t)s_M^+(t) \quad (15)$$

$$s_M^-(t) = s_M^+(t) - \sqrt{2}W_m v_m(t) \quad (16)$$

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:

$$W_m^T(t)W_m(t)v_m(t) - \sqrt{2}W_m^T(t)s_m^+(t) + F_{m_d}(t) = 0 \quad (17)$$

A possible simple strategy for finding the desired gain matrix is to choose a diagonal matrix $W_m(t) = diag(w_{m_1}(t), \ldots, w_{m_n}(t))$ and to solve (17) component-wise. In the following, for ease of notation, we will omit the subscripts m and M and we will provide a procedure for computing the gain $w_j(t)$ for achieving the component $F_{d_j}(t)$ of the desired force $F_d(t)$. The modulation algorithm is reported in Alg. Modulation.

Considering the j^{th} component, (17) becomes the following second order equation:

$$v_j(t)w_j^2(t) - \sqrt{2}s_j^+(t)w_j(t) + F_{d_j}(t) = 0 \quad (18)$$

Besides the desired force input $F_{d_j}(t)$, the incoming power wave that can be exploited $s_j^+(t)$ and the velocity output of the system $v_j(t)$ are required (Line 1). If $v_j(t) = 0$, (18) becomes $-\sqrt{2}s_j^+(t)w_j(t) + F_{d_j}(t) = 0$. A common case in which it is necessary to provide a force to the master even if its velocity is zero is during the interaction with rigid environments. If some power is coming from the slave side (Line 2) it is possible to reproduce the desired force by setting the modulation gain as shown in Line 3. If no power is coming from the slave side, nothing can be shaped and therefore we set $w_j = 1$ (Line 4), 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 $v_j \neq 0$ the gain w_j can be found by simply solving (18) which as a real solution only if its discriminant non negative, namely if $\frac{1}{2}(s_j^+(t))^2 - v_j(t)F_{d_j}(t) \geq 0$. 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. Thus, $\Delta E_j(t)$, the difference between the available power and the requested power is computed in Line 5. If the 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 (18) (Line 6). If $\Delta E_j(t) < 0$, it is still possible 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 computed (Line 7) in order to implement the force that is closest to the desired one. 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 $w_s(t)$ as:

$$\frac{\frac{1}{\sqrt{2}}s_j^+(t) \pm \sqrt{\frac{1}{2}(s_j^+(t))^2 - \alpha_j(t)v_j(t)F_{d_j}(t)}}{v_j(t)} = \frac{s_j^+(t)}{\sqrt{2}v_j(t)} \tag{19}$$

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

At the slave side, the incoming wave has to be exploited for computing a velocity input (impedance causality). From (5) with $b = 1$ and from(8) we get:

$$v_s(t) = -W_s^T(t)W_s(t)F_s(t) + \sqrt{2}W_s^T(t)s_S^+(t) \tag{20}$$

$$s_S^-(t) = -s_S^+(t) + \sqrt{2}W_s(t)F_s(t) \tag{21}$$

Since the structure of (20) is the same as that of (15), it is possible to do the same componentwise analysis done for (15) and to use Alg. Modulation for computing the componens of $W_s(t)$. Of course, the inputs to be used in Alg. Modulation are the desired velocity for the slave v_{d_j}, the incoming wave variable s_j^+ at the slave side and the force at the slave side F_{s_j}.

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, using (13) with (4) we have that:

$$F_m^T v_m = F_{m_d}^T v_m = F_M^T v_M = \frac{1}{2}\|s_M^+(t)\|^2 - \frac{1}{2}\|s_M^-(t)\|^2 \tag{22}$$

and, consequently $\frac{1}{2}\|s_M^-(t)\|^2 = \frac{1}{2}\|s_M^+(t)\|^2 - F_{m_d}^T v_m$. 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 [16]. 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 arises naturally: if some of the power of the incoming wave is not used, it is not dissipated through a matching damper as in [6], but it is sent back for being re-used.

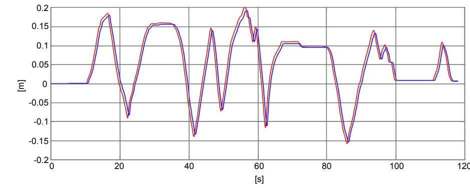
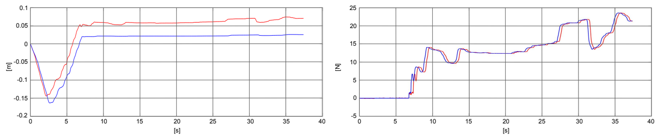


Fig. 3. Free motion. Master (red) and slave (blue) positions.

V. Experiments

The architecture proposed in Sec. III and in Sec. IV has been validated on a real teleoperation system using the Geomagic Touch haptic device and a gravity compensated Kuka Lightweight Robot 4+ as master and slave respectively. We teleoperated the slave along one DOF which is connected to a PD whose proportional and derivative gains are given by $K_p = 1000\ N/m$ and $K_d = 10\ Ns/m$ respectively. The communication delay between master and slave is $T = 300\ ms$, which is comparable to an intercontinental transmission delay (see e.g. [21]), and it is implemented using a circular buffer. The communication channel is passified through the strategy proposed in Sec. III. The delayed velocity of the master $\dot{x}_m(t - T)$ and the delayed force applied to the environment $F_e(t - T)$ are used as desired values for the slave and the master side respectively. In case of free motion, in order to avoid an energetic disconnection between master and slave, we set $F_{md} = -b_f\dot{x}_m$, with a small b_f. This is a velocity force architecture, which is known to be unstable for vey small time delays [3].

In Fig. 3 the performance of the teleoperation system in free motion are shown. It can be seen that, despite of the delay, the slave tracks the master very well and that no



(a) Interaction. Master (red) and slave (blue) positions.

(b) Force fed back to the master (red) and measured environment force (blue).

Fig. 4. Interaction experiment

oscillating transients (common in wave based teleoperation and due to the elastic dynamics of the communication channel) are present. The small tracking errors (e.g. around second 70) are due to the noise in the velocity measurements that are integrated by the PD controller. This is a problem common in this architecture (see e.g. [11]) and it can be solved using, e.g., [12] or by considering it in the definition desired velocity for the slave side. As it can be seen, by properly exploiting the incoming energy, it is possible to transfer the velocity of the master at the slave side without any intervening dynamic effect as it happens in standard wave based teleoperation. A further advantage is that by getting rid of the mass-spring dynamics of the wave based communication channel, we also get rid of its natural filtering behavior. In this way it is possible to track both slow and fast motions of the master at the slave side. In Fig. 4 the results of an interaction experiment are reported. The slave robot is moved toward a rigid environment and the user applies a variable force on the environment. In Fig. 4(a) it can be seen that when the slave meets the obstacle it stops in a stable way and after the master receives a force feedback, the user becomes aware of the obstacle and it stops as well. The small motions of the master are due to the variable force applied by the user and to the elasticity of the PD. As shown in Fig. 4(b), after the contact is established, force fed back to the master tracks the environment force with a good precision. Notice that, because the force is not fed back through the dynamics of the communication channel as it happens in standard wave based teleoperation, fast force variations are also properly tracked. In the multimedia attachment, a video of the experiments, where also the kinematic scaling between master and slave is taken into account, is available.

VI. Conclusions and Future Work

In this paper we have proposed a novel wave based teleoperation architecture that is as simple as standard wave based teleoperation, it just requires an algebraic manipulation for computing the coupling between master and slave, but that treats energy exchanges as in more recent teleoperation approaches, disembodying the energy exchange from unwanted physical dynamics. Experiments have proven the effectiveness of the proposed bilateral strategy. The proposed architecture allows to implement as better as possible, without violating the passivity constraint, the desired inputs dictated by a given transparency metric. A major topic for future research is to find a formal procedure for defining a proper transparency metric for a given task and to integrate energy tanks for further improving performance.

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