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Optimizing the use of power in wave based bilateral teleoperation

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Abstract— **Because of their simplicity, wave variables have become almost a standard strategy for stabilizing delayed bilateral teleoperation systems. However, the price to pay for a stable behavior is a degradation in the performance of the teleoperation system. Recently, more flexible and transparency oriented bilateral architectures have been proposed (e.g. TDPN, PSPM, Two-Layer approach) but they are complex to implement and to tune. In [1], a strategy for blending the high performance of the new control methodologies with the simplicity of wave based bilateral teleoperation has been proposed. Nevertheless, while appealing in terms of simplicity, this method is conservative in terms of the transparency that can be achieved. In this paper, we extend the architecture in [1] in order to optimize the use of the energy and for achieving a coupling that is as close as possible to the desired one while preserving the passivity of the overall system.**

I. Introduction

A bilateral teleoperation system consists of a user that interact with a master robot and a slave robot, that are interconnected by means of a bilateral control architecture which needs to have a stable behavior and to be transparent [2]. The motion of the master is sent to the slave that replicates it and the force between the slave and the remote environment is sent back to the master and felt by the user. Master and slave exchange information over a communication channel which is usually characterized by a non negligible delay that has a destabilizing effect on the overall system. Moreover, the slave can possibly interact with a poorly known environment. Both these issues have been major problems for the implementation of bilateral teleoperation systems since the early days of telerobotics [3].

Passivity theory and passivity based control have been successfully exploited for achieving a stable bilateral teleoperation system [4]. In particular, impedance control has been extensively used for stabilizing the interaction of the slave with the, possibly unknown, remote environment. For passifying the communication channel independently of the delay, several studies have been done. Scattering theory [5] and the wave variables method [6] have become almost a standard for stabilizing the delayed communication. Wave variables make the communication channel physically equivalent to a distributed mass-spring system. Such a physical dynamics is felt by the user, it influences the motion of the slave in an unplanned way and, consequently, it negatively affects the transparency of the teleoperation system.

More recently, more flexible and transparent coupling between master and slave have been proposed. In the Time Domain Passivity Network (TDPN) [7] the Passivity Observer/Passivity Controller (PO/PC) architecture is exploited for monitoring energy in real-time and dissipating the required amount of it. In the Passive Set-Point Modulation (PSPM) [8] energy reservoirs are used for implementing an energy aware scaling in a position-position architecture, while in the two-layer architecture [9] energy tanks were exploited for implementing any dynamic behavior without breaking the passivity constraint. Energy tanks have also been applied to surgical teleoperation [10], multi-slave teleoperation [11] and hybrid force/impedance control [12].

While these approaches are more efficient than the wave based teleoperation architecture since they do not introduce any unwanted dynamics, the associated architectures are more complex to implement and they require tuning of several parameters in an empirical way. In [1] the flexibility and efficiency of the new methodologies are blended with the simplicity of wave based architectures in order to achieve simple, passive and transparent bilateral teleoperation architectures. The idea is that of using the wave variables for storing the energy exchanged between master and slave and shaping the power contained in the incoming wave for getting the desired force/velocity. To this aim, a modulation strategy has been proposed and two gain matrices have been introduced in order to achieve the desired inputs for master and slave, completely overriding any natural dynamics of the communication channel. The problem of [1] is that the shaping was addressed componentwise. Treating each component separately brings some conservatism and leads to a suboptimal solution. In fact, even if there was enough power for implementing the desired force/velocity, if a component of the incoming wave did not contain sufficient power for implementing the corresponding component of the force/velocity, then a scaling was introduced. This leads to unnecessary deformations of the implemented force/velocity.

In this paper, we aim at extending the results of [1] in order to better exploit the gain matrices to improve the transparency of the teleoperation system. In particular we aim at getting rid of a componentwise shaping in order to consider the shaping problem as a whole. In this way, a bad distribution of power in the power variable will not affect the performance as it did in [1]. Thus we formulate the problem of shaping the incoming power as a constrained optimization problem that we solve exploiting Lagrange multipliers. In this way it is possible to find the best force/velocities to be implemented on master and slave while maintaining the passivity of the overall system. However, since the focus of the paper is not the evaluation of the best transparency metric, we will assume a generic definition of transparency.

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II. PRELIMINARIES

In this section we will briefly summarize the transparency oriented wave based teleoperation architecture presented in [1] to introduce the main elements that will be exploited for developing the new strategy proposed in this paper. We will adopt the scattering formalism proposed in [13] and we will consider a constant communication delay. All the results that will be developed in the paper can be easily extended to other formalisms for denoting the waves. Time-varying delays, random delays or packet loss can be addressed by applying the strategy proposed in [14]. The formulation proposed in this paper would still work even in these cases.

The main idea proposed in [1] is to exploit a time-varying passivity preserving modulation for shaping the power contained in the incoming wave variable in order to achieve, possibly scaled, desired forces and velocities. The overall architecture of the teleoperation system is shown 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. The slave robot together with the impedance controller constitutes the slave side in Fig. 1. At the master side, the desired force to apply to the robot F_{md} is computed using the (delayed) force measured at the environment and other task related information. Similarly, at the slave side, the desired velocity for the robot v_{sd} is computed using the (delayed) velocity of the master and other task related information. The desired values are rendered, possibly scaled, by tuning the modulation and the values F_m and v_m are computed.

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). The slave can interact with the master through the controller and it 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.

The power variables of master and slave side are modulated through modulation blocks and then transformed using the standard wave based approach. The modulation blocks implement the following interconnections:

$$\begin{cases} v_M(t) = W_m(t)v_m(t) \\ F_m(t) = W_m^T(t)F_M(t) \end{cases} \qquad \begin{cases} v_s(t) = W_s^T(t)v_S(t) \\ F_S(t) = W_s(t)F_s(t) \end{cases} \tag{1}$$

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

The transformation for master port with admittance causality and slave port with impedance causality is given by:

$$\begin{cases} F_M(t) = \sqrt{2b}s_M^+(t) - bv_M(t) \\ s_M^-(t) = s_M^+(t) - \sqrt{2b}v_M(t) \end{cases} \qquad \begin{cases} v_S(t) = \sqrt{\frac{2}{b}}s_S^+(t) - \frac{1}{b}F_S(t) \\ s_S^-(t) = \sqrt{\frac{2}{b}}F_S(t) - s_S^+(t) \end{cases} \tag{2}$$

where $s_i^+(t)$ and $s_i^-(t)$, with $i = \{M, S\}$, are the power waves associated to the power port (F_i, v_i) and $b \in \mathbb{R}^+$ is the wave impedance. 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, it has been chosen $b = 1$. The gains $W_m(t)$ and $W_s(t)$, are matrices 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. In fact, as shown in [1], the overall teleoperation system is passive with respect to the pair $((F_h^T, F_e^T)^T, (\dot{x}_m^T, \dot{x}_s^T)^T)$, independently of the (time-varying) values of the gain matrices.

In [1], a simple strategy for tuning the gains $W_m(t)$ and $W_s(t)$ to achieve the desired (i.e. transparent) inputs for master and slave is proposed. At the master side in Fig. 1 the incoming wave has to be exploited for computing a force input (admittance causality). From the transformation given in (2), with $b = 1$ and from (1) it results that:

$$\begin{aligned} F_m(t) &= -W_m^T(t)W_m(t)v_m(t) + \sqrt{2}W_m^T(t)s_M^+(t) \\ s_M^-(t) &= s_M^+(t) - \sqrt{2}W_m(t)v_m(t) \end{aligned} \tag{3}$$

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 a desired input force $F_{m_d}(t)$ it is necessary to choose $W_m(t)$ such that:

$$W_m^T(t)W_m(t)v_m(t) - \sqrt{2}W_m^T(t)s_m^+(t) + F_{m_d}(t) = 0 \tag{4}$$

In a similar way, at the slave side the incoming wave has to be exploited for computing a velocity input (impedance causality). From (2), with $b = 1$ and (1) we get:

$$\begin{aligned} v_s(t) &= -W_s^T(t)W_s(t)F_s(t) + \sqrt{2}W_s^T(t)s_S^+(t) \\ s_S^-(t) &= -s_S^+(t) + \sqrt{2}W_s(t)F_s(t) \end{aligned} \tag{5}$$

As for the admittance causality 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:

$$W_s^T(t)W_s(t)F_s(t) - \sqrt{2}W_s^T(t)s_S^+(t) + v_{s_d}(t) = 0 \tag{6}$$

The strategy proposed in [1] for finding the desired gain matrices is 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 (4) and (6) componentwise. In this way, (4) and (6) become second order equations that can be easily solved for finding possible values of each component of $W_m(t)$ and $W_s(t)$. The desired force and velocity at the master and slave side respectively, can be achieved only if the power requested for implementing the j-th component of $F_{m_d}(t)$ and $v_{s_d}(t)$ is not greater than the power contained in the incoming power waves, that means:

$$\begin{aligned} \tfrac{1}{2}(s_{M_j}^+(t))^2 - v_{m_j}(t)F_{m_{dj}}(t) \geq 0 \\ \tfrac{1}{2}(s_{S_j}^+(t))^2 - F_{s_j}(t)v_{s_{dj}}(t) \geq 0 \end{aligned} \tag{7}$$

However, if the incoming power is not sufficient for implementing the desired force/velocity, it is still possible to realize a scaled version of the desired values in order to achieve a possible approximation of the j-th component of $F_{m_d}(t)$ and $v_{s_d}(t)$ compatible with the passivity constraint.

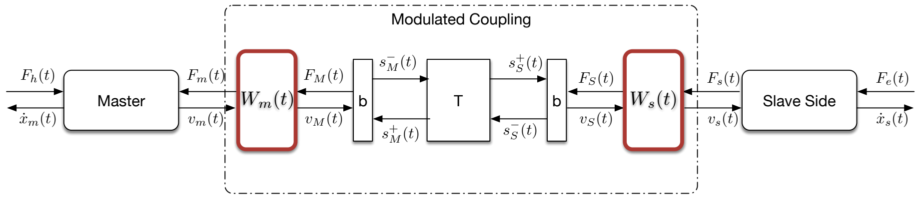


Fig. 1. The overall architecture

III. 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. As proposed in [1], 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,

In this section, we will introduce an optimization problem for choosing the best force/velocity to implement at the master/slave side while using at most the power contained in the incoming wave variable.

A. Master and slave minimization problems

Consider the master side and let

$$F_{m_d}(t) = \phi_m(F_e(t-T), v_m(t)) \in \mathbb{R}^n \tag{8}$$

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 $v_m(t)$ (e.g. if the goal is to directly reflect the force exerted by the environment, $\phi_m = F_e(t-T)$).

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:

$$\begin{aligned} &\text{minimize} && \|F_m(t) - F_{m_d}(t)\|^2 \\ &\text{subject to} && F_m^T(t) v_m(t) \le \frac{1}{2}\|s_M^+(t)\|^2 \end{aligned} \tag{9}$$

where $F_m(t)$ is the variable that has to be optimized and

$$\|F_m(t) - F_{m_d}(t)\|^2 = F_m^T(t)F_m(t) - 2F_m^T(t)F_{m_d}(t) + F_{m_d}^T(t)F_{m_d}(t) \tag{10}$$

Consider now the slave side and let

$$v_{s_d}(t) = \phi_s(v_m(t-T), F_s(t)) \in \mathbb{R}^n \tag{11}$$

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 $F_s(t)$.

As for the master 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:

$$\begin{aligned} &\text{minimize} && \|v_s(t) - v_{s_d}(t)\|^2 \\ &\text{subject to} && v_s^T(t) F_s(t) \le \frac{1}{2}\|s_S^+(t)\|^2 \end{aligned} \tag{12}$$

where $v_s(t)$ is the variable that has to be optimized and

$$\|v_s(t) - v_{s_d}(t)\|^2 = v_s^T(t)v_s(t) - 2v_s^T(t)v_{s_d}(t) + v_{s_d}^T(t)v_{s_d}(t) \tag{13}$$

In order to formulate (9) in the standard optimization formalism, we set for the master side:

$$F_m(t) =: x = (x_1 \dots x_n)^T \qquad F_{m_d}(t) =: a = (a_1 \dots a_n)^T$$

$$v_m(t) =: b = (b_1 \dots b_n)^T \qquad \tfrac{1}{2}\|s_M^+(t)\|^2 =: \sigma \tag{14}$$

Similarly, to formulate (12) 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, using (14), both (9) and (12) can be formalized as quadratic optimization problems with a linear constraint:

$$\begin{aligned} &\text{minimize} && \sum_{i=1}^{n} x_i^2 - 2a_i x_i + a_i^2 \\ &\text{subject to} && \sum_{i=1}^{n} b_i x_i - \sigma \le 0 \end{aligned} \tag{15}$$

B. Solution of the general optimization problem

The problem (15) 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 (15) 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:

$$\sum_{i=1}^{n} b_i a_i - \sigma \leq 0 \tag{16}$$

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 [15]. Thus, we first build the following augmented functional, where $\lambda \geq 0$:

$$J_A = \sum_{i=1}^{n} x_i^2 - 2a_i x_i + a_i^2 + \lambda\left(\sum_{i=1}^{n} b_i x_i - \sigma\right) \tag{17}$$

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 (15), such that

$$\begin{pmatrix} \frac{\partial J_A}{\partial x} & \frac{\partial J_A}{\partial \lambda} \end{pmatrix}^T = 0 \tag{18}$$

which implies:

$$\underbrace{\begin{pmatrix} 2I_n & b \\ b^T & 0 \end{pmatrix}}_{M} \begin{pmatrix} x^\star \\ \lambda^\star \end{pmatrix} = \begin{pmatrix} 2a \\ \sigma \end{pmatrix} \tag{19}$$

By using the invertibility formula for block matrices, it is easy to verify that M is always invertible if and only if $b \neq 0$. Notice that if $b = 0$, then (16) 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:

$$\begin{pmatrix} x^\star \\ \lambda^\star \end{pmatrix} = M^{-1} \begin{pmatrix} 2a \\ \sigma \end{pmatrix} \tag{20}$$

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

IV. Optimal wave based teleoperation

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. In this section we will see how the solution of the optimal problem can be used for tuning the modulation matrices $W_m(t)$ and $W_s(t)$ in order to remove the conservatism introduced in [1] by considering each component separately in the energetic analysis. In fact, checking the constraints (7) for each component means that the force/velocity implemented could be scaled without taking into consideration the global power available. Exploiting the optimal strategy presented in Sec. III, the total incoming power is taken into account and it can be redistributed on all the components depending on the real power request.

Procedure Optimization

Data: $F_{m_d}(t), s_M^+(t), v_m(t), W_m(t^-)$

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

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

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

4 $\quad F_m^\star(t) = F_{m_d}(t)$

else

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

6 $\quad \begin{pmatrix} F_m^\star(t) \\ \lambda^\star(t) \end{pmatrix} = M^{-1} \begin{pmatrix} 2F_{m_d}(t) \\ \sigma(t) \end{pmatrix}$

7 $v_M(t) = W_m(t^-) v_m$

8 $F_M(t) = \sqrt{2} s_M^+(t) - v_M(t)$

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

9 $\quad$ **if** $F_{M_j}(t) \neq 0$ **then**

10 $\quad\quad w_{m_j}(t) = \frac{F_{m_j}^\star(t)}{F_{M_j}(t)}$

$\quad$ **else**

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

12 $W_m(t) = diag(w_{m_1}(t), \ldots, w_{m_n}(t))$

13 $F_m(t) = W_m(t)^T F_M(t)$

14 $s_M^-(t) = s_M^+(t) - \sqrt{2} W_m(t) v_m(t)$

Let $F_m^\star(t)$ and $v_s^\star(t)$ be the optimal solutions computed by solving the optimization problems reported in Sec. III. According to the wave variable approach, we can compute the variables $F_M(t)$ and $v_S(t)$ using (2). Then, by considering the modulation blocks (1) we can state the following relations between the optimal values to be implemented and the standard wave variables.

$$F_m^\star(t) = W_m^T(t) F_M(t) \qquad v_s^\star(t) = W_s^T(t) v_S(t) \tag{21}$$

We keep on considering diagonal modulation matrices as in Sec. II, since this is the simplest way for being able to act on every dimension. Each component on the diagonal is computed as:

$$w_{m_j}(t) = \frac{F_{m_j}^\star(t)}{F_{M_j}(t)} \qquad w_{s_j}(t) = \frac{v_{s_j}^\star(t)}{v_{S_j}(t)} \tag{22}$$

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[1] (3) and (5). 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 is reported in Alg. Optimization.

Besides the desired force input $F_{m_d}(t)$, the incoming power wave that can be exploited $s_M^+(t)$, the velocity output of the system $v_m(t)$ and the previous gain matrix $W_m(t^-)$ are required (Line 1). 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 problem

[1]as shown in [1], using the proposed approach wave reflection is not a problem and, therefore, no countermeasure for preventing it has to be taken

is to check if the passivity constraint (16) 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. III, the matrix M is computed according to (19) (Line 5) and the solution of the optimization problem is found from (20) (Line 6). Then, the variables $v_M(t)$ and $F_M(t)$ are computed using the standard wave variable theory according to (2) (Lines 7 and 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 (21) 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 and Alg. Optimization can be applied. The only differences are 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 input $s_M^+(t)$ and $W_m(t^-)$ are substituted by $s_S^+(t)$ and $W_s(t^-)$, respectively.

V. Experiments

We performed experimental tests on a real teleoperation system in order to validate the teleoperation architecture presented in this paper. We tried to perform an experiment similar to the one shown in [1] in order to compare the performance achieved by each architecture. The Geomagic Touch haptic device[2] was utilized as master device, while a gravity compensated Kuka Lightweight Robot 4+[3] has been used as slave robot. Since the proposed architecture does not treat each DOF separately but it considers the power exchange as a whole, we cannot teleoperate the robot only along one cartesian direction as we did in [1]. Since the orientation DOFs of the Geomagic Touch device are not actuated and, therefore, the reaction moments cannot be reflected to the user, we teleoperate the slave robot along the translation components, without considering the orientation. However, this practical limitation does not affect the generality of the approach described in the paper.

The slave robot 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. [16]), and it is implemented using a circular buffer.

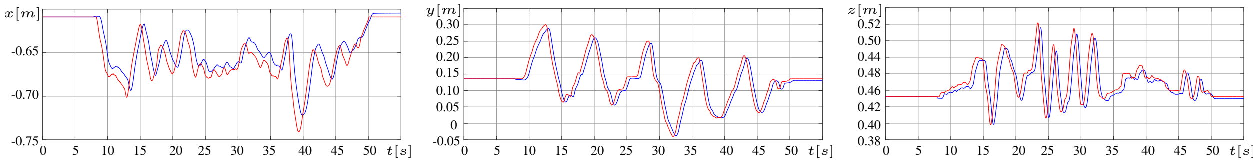
The desired velocity for the slave is the velocity of the master, available after T seconds, while the desired force for the master device is the force that the environment applies to the slave, available after T seconds. The velocity and the force to be implemented, respectively, at the slave and master robots are computed through the resolution of the optimization problem presented in Sec. III. In case of free motion, implementing a zero force would cause an energetic disconnection of the master and of the slave, and thus in free motion we implemented a small viscous force. Furthermore, despite of the kinematic difference, we have implemented no scaling between master and slave. In this way the performance of the architecture can be better appreciated in the following plots.

In [1] we have already shown that, despite of the delay, the slave can track the master position very well and no oscillating transients are present. Figure 2 shows the performance of the teleoperation system in free motion using the approach described in Sec. III and Sec. IV. It can be seen that even the new approach allows the slave to correctly track the master motion. The small tracking errors are due to the noise in the velocity measurements that are integrated by the PD controller. This problem can be solved using standard strategies as, e.g., [17].

Moreover, in [1] we have shown that 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. Now, we want to show the improvement in the transparency of the teleoperation system that can be obtained applying the strategy proposed in this paper for tuning the gain matrices and compute the optimal force/velocity to implement. In the experiment, the slave robot is moved towards a rigid environment and the user applies a variable force on the environment.

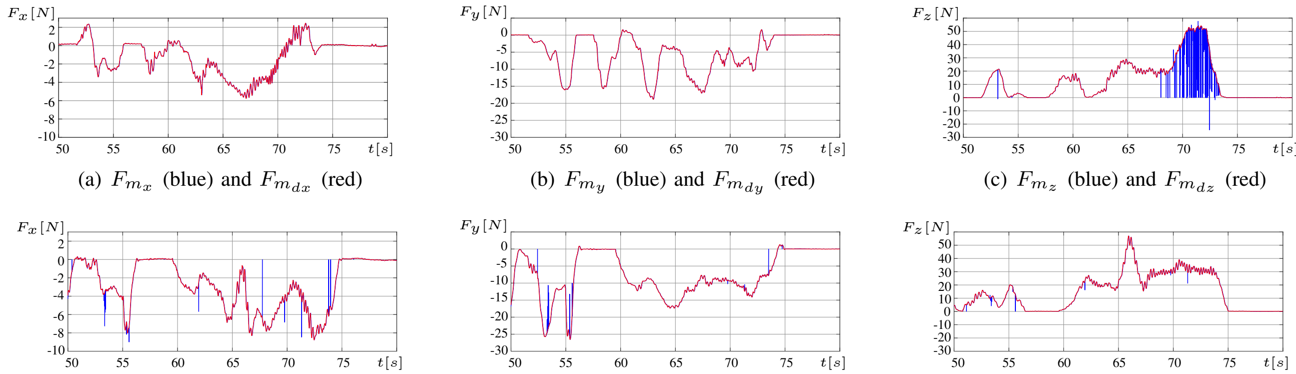
In Fig. 3 the comparison between the forces fed back to the master during the interaction using the approach described in [1] and using the approach described in this paper is shown. The slave meets the obstacle mainly along the z direction. By using the componentwise approach described in [1], the forces along the x and y directions (Fig. 3(a) and 3(b)) are not scaled because the power available is sufficient to passively implement the desired force along these components, while the force along the z direction is drastically scaled 3(c). However, if the total power available is enough for implementing the force, this solution is suboptimal since it leads to an unnecessary deformation of the implemented force. Indeed, the plots on the right in Fig. 3 show that the previous scaling is not necessary if the shaping problem is considered as a whole. The scaling along z is no more required (Fig. 3(f)) since the available power is redistribute along all the components thanks to the resolution of the optimization problem described in Sec. III and Sec. IV.

[2] http://www.geomagic.com/en/products/phantom-omni/overview
[3] http://www.kuka-robotics.com/en



(a) x master (red) and x slave (blue) (b) y master (red) and y slave (blue) (c) z master (red) and z slave (blue)

Fig. 2. Positions of the master device (red lines) and of the slave robot (blue lines) in free motion.



(a) F_{m_x} (blue) and $F_{m_{dx}}$ (red) (b) F_{m_y} (blue) and $F_{m_{dy}}$ (red) (c) F_{m_z} (blue) and $F_{m_{dz}}$ (red)

(d) F_{m_x} (blue) and $F_{m_{dx}}$ (red) (e) F_{m_y} (blue) and $F_{m_{dy}}$ (red) (f) F_{m_z} (blue) and $F_{m_{dz}}$ (red)

Fig. 3. Force fed back to the master (blue lines) and measured environment force (red lines) using the approach described in [1] (top plots) and using the new optimization method proposed in this paper (bottom plots).

VI. Conclusions and Future Work

In this paper, we extended the results obtained in [1], where a strategy for blending the flexibility and efficiency of recently proposed bilateral teleoperation architectures with the simplicity of wave based architectures was proposed in order to achieve simple, passive and transparent bilateral teleoperation architecture even in presence of communication time-delay. In particular, we got rid of a componentwise shaping of the incoming wave, which brings to suboptimal solutions, and consider the shaping problem as a whole. An optimization problem was formulated and solved in order to find the optimal force/velocity to be implemented that is closest to the desired one. Experiments have been performed to prove the effectiveness of the proposed bilateral strategy.

The experiments show that the behavior of the teleoperation system is as expected. However, when the force scales it present some spikes, due to the optimization process. Future works aim at removing these spikes.

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