Transparency in Port-Hamiltonian-Based Telemanipulation

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***Abstract*—After stability, transparency is the major issue in the design of a telemanipulation system. In this paper, we exploit the behavioral approach in order to provide an index for the evaluation of transparency in port-Hamiltonian-based teleoperators. Furthermore, we provide a transparency analysis of packet switching scattering-based communication channels.**

***Index Terms*—Port-Hamiltonian systems, telemanipulation, transparency.**

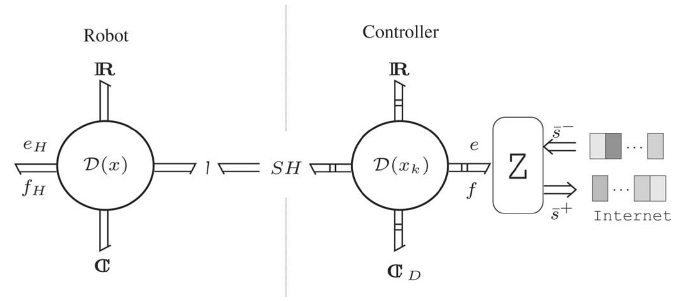

Fig. 1. Passive sample data telemanipulation scheme.

I. Introduction

Passivity is a very suitable tool to stabilize a telemanipulator. Implementing each part of a telerobotic system as a passive system and interconnecting them in a passive way, it is possible to achieve an intrinsically passive system that is consequently characterized by a stable behavior. In passivity-based telemanipulation, the robots are controlled by passive controllers, which allow a stable interaction of the system with any passive, possibly unknown, environment. Master and slave sides are interconnected by means of a scattering-based communication channel [1], [10] that allows a passive exchange of energy independent of any constant transmission delay. Thus, the overall telemanipulation system is passive, and consequently, characterized by a stable behavior.

Several passivity-based telemanipulation systems have been proposed in the literature, see e.g., [8] for a recent review. The port-Hamiltonian framework has been successfully applied to the control of passivity-based teleoperators, as reported in [16], [18], and [19]. Within this framework, both master and slave robots, which are modeled as port-Hamiltonian systems, are controlled by an intrinsically passive port-Hamiltonian impedance controller (IPC) that allows to implement both linear and nonlinear impedances. Master and slave sides are interconnected by means of a geometric scattering-based communication channel.

Intrinsic passivity, and therefore, a stable behavior, is only a *first* necessary step toward the implementation of a telemanipulation system. In fact, performances have to be taken into account to make a telerobotic system effective and useful for real applications. After stability, *transparency* is the major issue in teleoperation systems design. The better the operator at the master side feels to interact directly with the remote environment, the better a telemanipulator behaves. The whole telemanipulation system (robots, controllers, and communication channel) should ideally be *transparent* and the operator should not feel its presence at all.

Several researches addressed the problem of transparency. Transparency is defined as a correspondence between master and slave positions and forces in [20] while as a match between the impedance perceived by the operator and the environment impedance in [9]. Furthermore, several telemanipulation schemes that optimize transparency have been proposed and most of them consider the case in which master and slave side dynamics are linear, see, for example, [3], [5], and [6].

This research is an extended version of [14] and its aim is twofold. First, we want to provide a framework for the evaluation of transparency for generic, possibly nonlinear and delayed, port-Hamiltonian-based telemanipulators. Using the concept of *port behavior* [17], it is possible to obtain an index that measures how much realistic the feeling perceived by the user is when he/she is interacting with the remote environment by the telemanipulator. Analogously to what happens for the design of an intrinsically passive telemanipulation system, it is possible to split the design of a transparent telemanipulator into the transparency optimized design of its parts. Thus, second, we want to study the transparency of discrete scattering-based packet switching communication channel proposed in [18]. We will study the effects of delay and of the scattering coding of power variables on the transparency of the interconnection between master and slave sides. We will also analyze the effects of phenomena typical of switching packet networks such as packets loss and variable communication delay. The paper is organized as follows. In Section II, some background on port-Hamiltonian-based telemanipulation and on port behavior is provided, in Section III, the transparency framework is developed and a measure for evaluating transparency is proposed. In Section IV, the transparency of the digital scattering-based communication channel is analyzed, and in Section V, some simulations are proposed in order to validate our results. Finally, in Section VI, conclusions are reported and some future work is addressed.

II. Background

A. Port-Hamiltonian-Based Telemanipulation

Port-Hamiltonian systems are a mathematical formalization of the network modeling paradigm for physical system. They are composed by a state manifold $\mathcal{X}$, by a lower bounded energy function $H : \mathcal{X} \mapsto \mathbb{R}$, representing the energy stored in a given configuration, and by a skew-symmetric matrix $D(x)$ that represents the internal network structure along which all the components of the system exchange energy. A port-Hamiltonian system can be endowed with power ports, represented by pairs of dual power variables $(e, f) \in E \times F$, which are called effort and flow, respectively. These ports are used to energetically interact with the system and the power supplied through a power port is equal to $e^T f$. These systems allow to model a very broad class of physical systems, both linear and nonlinear. For a more detailed treatment, see [16].

It is possible to use port-Hamiltonian systems to build an intrinsically passive bilateral telemanipulation system over packet switched communication networks. One side of a port-Hamiltonian-based telemanipulation scheme is illustrated in Fig. 1 in a bond-graph notation where barred bonds represent a discrete exchange of energy.

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The robot, which can be modeled as a port-Hamiltonian system, is interconnected in a power preserving way [by means of the sample and hold (SH) device proposed in [18]] to a discrete passive impedance controller (represented by a discretized port-Hamiltonian system). Master and slave sides exchange energy through a packet switching scattering-based communication channel and they are interconnected to the transmission line through the discrete power ports $[e_m(k), f_m(k)]$ and $[e_s(k), f_s(k)]$, respectively. Each discrete power port can be decomposed into a pair of scattering variables defined as

$$\begin{cases} s_i^+(k) = \dfrac{1}{\sqrt{2}} N^{-1}(e_m(k) + Zf_m(k)) \\ s_i^-(k) = \dfrac{1}{\sqrt{2}} N^{-1}(e_m(k) - Zf_m(k)) \end{cases}, \qquad i = m, s \tag{1}$$

and $Z = NN > 0$ is the impedance of the scattering transformation [19]. We can interpret $s_i^+(k)$ and $s_i^-(k)$ as an incoming and an outgoing power packet, respectively [18]. Every sample period, at each side, the system reads the incoming power packet $s_i^+(k)$ and the discrete effort $e_i(k)$ and calculates the outgoing energy packet $s_i^-(k)$ and the discrete flow $f_i(k)$.

Master and slave sides exchange power through the scattering variables and the communication strategy used in port-Hamiltonian-based telemanipulation is given by

$$\begin{cases} s_s^+(k) = s_m^-(k - \delta) \\ s_m^+(k) = s_s^-(k - \delta) \end{cases} \tag{2}$$

where δ is the communication delay between master and slave and *vice versa*. In this way, the communication channel becomes lossless and the overall telemanipulation system, which is given by the interconnection of the passive master and slave sides through a lossless transmission line, is intrinsically passive, and consequently, characterized by a stable behavior.

Due to the port-Hamiltonian formalism, it is possible to model telemanipulation systems characterized both by linear and nonlinear robots, and it is possible to implement both linear and nonlinear impedance controllers. Furthermore, in port-Hamiltonian-based telemanipulation, master and slave sides exchange information by means of a geometric scattering-based communication channel [16] that allows to transmit *any* dual geometric objects (as twists and wrenches that can be modeled as matrices or even parameters characterizing the impedance controllers of master and slave sides [16]) and not only vectors. Furthermore, the port-Hamiltonian structure makes evident that the energy flows among the various components of the system making it suitable for the analysis and the synthesis of passive telemanipulation systems. For further details, see [16], [18], and [19].

B. Port Behavior

Consider a port-Hamiltonian system characterized by a state manifold $\mathcal{X}$ and endowed with a power port $(e, f) \in E \times F$ through which it can exchange energy with the rest of the world. The *port outcomes space*, namely the space on which the flows, the efforts, and the configurations of the system live, is defined as $W = E \times F \times \mathcal{X}$. Using the concepts developed in [17], it is possible to determine the states of the system that are compatible[1] with a particular effort–flow configuration. It is then possible to define the *universe of port outcomes* as the set

$$\mathcal{U} = \{(x, f, e) \in W^{\mathcal{T}} \mid x \text{ is compatible with the pair } (e, f)\} \tag{3}$$

[1]A configuration x is compatible with an effort–flow pair if, fixed one power variable (either the effort or the flow) as an input, it is possible for the system at the configuration x to produce the other power variable as an output. For a more formal treatment, see [17].

where $\mathcal{T}$ is an ordered time space.[2] The universe of port outcomes is the set of *all* possible trajectories that can be described in W by the system.

A *port behavior* is defined as a certain $\mathcal{B} \subset \mathcal{U}$ of compatible port outcomes, namely a particular subset of trajectories that the system is allowed to describe in W.

The port behavior can be described by means of differential equations using the concept of *port jet space* [17]. Let $\mathcal{G}$ be a manifold and $g(\cdot) \in \mathcal{G}^{\mathcal{T}}$, a sufficiently smooth function. Let $\mathcal{G}_i$ denote the set of all possible instantaneous ith temporal derivatives for any possible $g(\cdot)$. The set $\mathcal{G}^{(n)} = \mathcal{G} \times \mathcal{G}_1 \times \cdots \times \mathcal{G}_n$ is well defined and points in $\mathcal{G}^{(n)}$ are indicated as $g^{(n)}$. Consequently, for any sufficiently smooth function $g(\cdot) \in \mathcal{G}^{\mathcal{T}}$, there is an induced function $g^{(n)}(\cdot) = pr^{(n)} g(\cdot)$ called the nth *prolongation of* $g(\cdot)$ that is defined by $g^{(n)}(t) = (g(t), g_1(t), \ldots, g_n(t))$, where $g_i(\cdot)$ is the ith temporal derivative of $g(\cdot)$. Thus, $pr^{(n)} g(\cdot)$ is a function from the time set $\mathcal{T}$ to $\mathcal{G}^{(n)}$. The *extended* nth-*order port jet space* is defined to be the space $\mathcal{T} \times W^{(n)}$. Under suitable mild conditions (see [17]), a port behavior $\mathcal{B}$ can be described by a continuous function $\Delta^{\mathcal{B}} : \mathcal{T} \times W^{(n)} \to \mathbb{R}^v$. The behavior is equivalent to the set

$$S_{\Delta^{\mathcal{B}}} = \{(t, w) | \Delta^{\mathcal{B}}(t, pr^{(n)} w) = 0\} \tag{4}$$

namely to the kernel of the operator $\Delta^{\mathcal{B}}(\cdot, \cdot)$. Notice that the concept of port outcome and of port behavior are very general, and therefore, they can be used for the study of both linear and nonlinear telemanipulation systems. For further details, see [12] and [17].

III. Measure for Transparency

Two main power ports can be distinguished in a port-Hamiltonian-based telemanipulation system: the environment port (e_E, f_E), through which the telemanipulator interacts with the remote environment, and the human port (e_H, f_H), by means of which the operator interacts with the system. Between these interaction ports, there is the telemanipulator made up of the robots, their controllers, and the communication channel. The feeling that the human operator perceives is due neither only on the effort dynamics nor only on the flow dynamics. It depends on the dynamical relationships between e_H and f_H, namely on the port behavior (or, in other words, on the evolution of the port outcome), which represents the energy that the human exchanges with the system. A telemanipulation system is perfectly transparent if the power variables of the environment port (e_E, f_E) and those of the human port (e_H, f_H) have the same dynamic relationship. In this case, the feeling the human operator perceives is exactly the same as if he/she would be directly interacting with the remote environment.

Each component of the telemanipulation system introduces spurious effects that are deleterious for transparency. Master and slave robots interpose their dynamics between the human and the environment and the communication channel introduces undesired features in the interconnection between master and slave sides, such as transmission delay and packets loss. The role of control is to minimize these effects to maximize transparency that has to be measured in some way. In order to evaluate the transparency of a telemanipulation system, it is necessary to measure the difference between the behaviors of the ports (e_H, f_H) and (e_E, f_E). In the ideal case of perfect transparency, the two behaviors should perfectly match. In case of linear telemanipulators characterized by a constant communication delay, it is possible to use classical concepts of impedance control to measure the match between the port behaviors through, for instance, H_∞ norm. Unfortunately,

[2]The notation $\mathcal{P}_2^{\mathcal{P}_1}$ indicates the set of maps from the set $\mathcal{P}_1$ to the set $\mathcal{P}_2$.

very often telemanipulators are characterized by nonlinear dynamics (e.g., if master and slave are anthropomorphic robots). Furthermore, being the Internet used more and more frequently for implementing the communication, the delay is often variable and characterized packets loss. Thus, it is necessary to give a more general measure of transparency and the behavioral approach and the concept of port behavior described in the previous section provide a suitable framework for this analysis.

Let $\mathcal{B}$ be a certain desired port behavior described by $\Delta^{\mathcal{B}}$ and $w(t)$ a port outcome measured at time t. The *behavioral deviation* at time t of $w(\cdot)$ from the behavior $\mathcal{B}$ is defined to be

$$\|\Delta^{\mathcal{B}}(t, pr^{(n)} w(t))\| \tag{5}$$

where $\|\cdot\|$ is the Euclidean norm of $\mathbb{R}^v$. Loosely speaking, (5) represents how much the port outcome $w(\cdot)$ is out of the kernel of $\Delta^{\mathcal{B}}$ and, namely, how much it deviates from the behavior $\mathcal{B}$.

The behavior of the environment port is determined by the dynamics of the remote environment. Let $\mathcal{E} \subset \mathcal{U}$ be the port behavior of the environment described by $\Delta^{\mathcal{E}}$ and let w_H be the port outcome at the port (e_H, f_H). A telemanipulation system is *perfectly transparent* if

$$\Delta^{\mathcal{E}}(t, pr^{(n)} w_H(t)) = 0 \tag{6}$$

namely if the behavior of the environment port is exactly reproduced at the human port. A measure of nontransparency is given by the deviation of the human port from the behavior $\mathcal{E}$. The following *transparency deviation index* can be defined.

Definition 1: The transparency deviation index ε is defined by the following relation:

$$\varepsilon(t) = \|\Delta^{\mathcal{E}}(t, pr^{(n)} w_H(t))\|. \tag{7}$$

In case of perfect transparency, $\varepsilon(t) = 0 \; \forall t \in \mathcal{T}$.

Transparency and the transparency deviation index are very general concepts valid for both linear and nonlinear systems since no assumption is made on the structure of the telemanipulator. It follows from the definition that in order to evaluate transparency deviation, a model of the environment is necessary. This is the main limitation of our approach. Nevertheless, while the particular environment the system will interact with is not always known, a class of environments is often known (e.g., soft environments, that can be modeled through the Hunt–Crossley model, [4]). Thus, it is possible to evaluate the maximum transparency deviation within the given class and to exploit the proposed framework to design control algorithms that minimize the worst-case transparency deviation. Free motion of the slave can be interpreted as the interaction with a particular environment whose behavior can be characterized by the equation $e_E = 0$ for all the possible flows.

The transparency deviation index depends on the port outcome that, as reported in (3), contains both an effort–flow pair information and the state information of the system it refers to. Thus, the proposed transparency index can capture both power- and configuration-based information and it can also take into account position errors that can arise in passivity-based teleoperation.

A port-Hamiltonian-based bilateral telemanipulation system can be split into three parts interconnected through power ports. Thus, the design of a transparent telemanipulation system can be split into three subproblems: the design of transparent master and slave sides and the design of a transparent communication channel. The proposed framework can be used to separately evaluate transparency of the various subsystems. Thus, even if no model of the environment is available, it is still possible to exploit the proposed framework to evaluate transparency of parts of the telemanipulation system and to use it as a guide for the transparency optimized design of each part. In fact, it is possible to identify a particular ideal behavior that a certain component of a telemanipulation system (e.g., the communication channel) should have and to evaluate transparency of this component as the behavioral deviation of the system from the ideal behavior.

Remark 1: In the paper, we consider symmetric telemanipulation systems, where master and slave robots are of the same mechanical structure, and consequently, the human and the environment ports have the same dimension. Nevertheless, the proposed framework can also be extended in case master and slave have different structures, namely in case the user can move and perceive the interaction of the slave only along some directions. In this case, the higher dimensional port has to be projected along the directions of the lower dimensional port. In this way, it is possible to exploit Definition 1. In other words, this means to evaluate transparency along the direction where the user can perceive the interaction with the remote environment.

IV. Transparency Analysis of a Scattering-Based Packet Switching Channel

Consider the port-Hamiltonian-based telemanipulation system described in Section II-A. Master and slave sides exchange energy through the communication channel to which they are connected by means of the discrete power ports $[e_m(k), f_m(k)]$ and $[e_s(k), f_s(k)]$, respectively. In case of negligible communication delay, the interconnection between local and remote sides can be made through the so-called *common effort interconnection*, which is given by

$$\begin{cases} e_m(k) = e_s(k) \\ f_s(k) = -f_m(k). \end{cases} \tag{8}$$

This interconnection can be causally achieved if, for example, the master controller has an admittance causality (effort in/flow out) and the slave controller has an impedance causality (flow in/effort out). Using (8), we have that

$$P_s(k) = e_s^T(k) f_s(k) = -e_m^T(k) f_m(k) = P_m(k) \tag{9}$$

namely that the energy provided at the slave side at the time k is equal to that extracted from the master side at the same instant. Thus, in this ideal case, master and slave would directly exchange energy without any delay and without any loss of information. In case of nonnegligible communication delay, the strategy reported in (8) cannot be used since it would destabilize the overall telemanipulation system, as proven in [10]. Combining (1) with (8), the common effort interconnection can be equivalently restated in terms of scattering variables as

$$\begin{cases} s_m^+(k) = s_s^-(k) \\ s_s^+(k) = s_m^-(k). \end{cases} \tag{10}$$

As proven in [18], this communication strategy can also be safely used in case of nonnegligible delay leading to the interconnection reported in (2).

Thus, the scattering theory can be used to allow a nondestabilizing exchange of energy between master and slave. Nevertheless, both transmission delay and the scattering coding/decoding procedure, necessary to compute $f(k)$ and $s^+(k)$ from $e(k)$ and $s^-(k)$ as described in Section II-A, introduce some deleterious effects on transparency of the communication channel.

Remark 2: In telemanipulation schemes where the communication channel has an admittance causality (effort in/flow out) both at master and slave sides, the absence of delay leads to causality problems, as reported in [10] and [19]. The transparency analysis that follows can be adapted in order to include this case by simply considering an infinitesimal delay at the corresponding power interconnection as an ideal case.

The aim of this section is to provide a transparency analysis of the discrete scattering implementation of switched packets communication channel for port-Hamiltonian-based telemanipulation described in [18] using the framework proposed in Section III. This kind of communication channel can also be used for interconnecting master and slave sides of generic passivity-based telerobotic systems, and therefore, the following considerations are useful also for nonport-Hamiltonian-based telemanipulation schemes.

The ideal port behavior $\mathcal{I}$ that guarantees a completely transparent interconnection between the master and the slave sides (and consequently, a completely transparent communication channel) is given by the common effort interconnection. Using (8), the ideal port behavior can be represented as the kernel of the following operator:

$$\Delta^{\mathcal{I}}(k, f_m(k), f_s(k), e_m(k), e_s(k)) = \begin{pmatrix} f_m(k) + f_s(k) \\ e_s(k) - e_m(k) \end{pmatrix} \qquad (11)$$

where the port outcome reduces to

$$(f_m(k), f_s(k), e_m(k), e_s(k))$$

since the interconnection is not characterized by a configuration. Notice that this is a degenerate case of port behavior since it is simply represented by an algebraic relation between the power variables. It is possible to evaluate the transparency of the transmission line as the behavioral deviation from the ideal behavior $\mathcal{I}$ when the communication delay is present.

Using (11), we are able to define the transparency of the communication channel not simply as a match between forces and velocities but as a deviation from the ideal role it should have in interconnecting master and slave, namely that of instantaneously transferring energy. This allows a clear interpretation, in terms of transparency deviation, of phenomena like packets loss and variable communication delay that can cause energy dissipation. From a comparison between forces and velocities, it is not possible to clearly represent the effects of these energetic phenomena. Furthermore, considering flows and efforts, it is possible to handle not only force and velocity vectors but, more generally, dual variables. Thus, the proposed analysis can be used to evaluate any exchange of energetic information along a packet switching channel.

Using (1) in (2), by lengthy but straightforward computations, the communication strategy can be equivalently restated in terms of efforts and flows as

$$\begin{cases} f_s(k) = -f_m(k) + (f_m(k) - f_m(k-\delta)) \\ \qquad\quad + Z^{-1}(e_m(k-\delta) - e_s(k)) \\ e_m(k) = e_s(k) - (e_s(k) - e_s(k-\delta)) \\ \qquad\quad - Z(f_m(k) + f_s(k-\delta)). \end{cases} \qquad (12)$$

Thus, using (12) in (11) and applying Definition 1, the transparency deviation index evaluated for the delayed scattering-based communication channel is given by

$$\varepsilon = \left\| \begin{pmatrix} (f_m(k) - f_m(k-\delta)) + Z^{-1}(e_m(k-\delta) - e_s(k)) \\ (e_s(k) - e_s(k-\delta)) + Z(f_m(k) + f_s(k-\delta)) \end{pmatrix} \right\|$$
$$\leq \underbrace{\left\| \begin{pmatrix} (f_m(k) - f_m(k-\delta)) \\ (e_s(k) - e_s(k-\delta)) \end{pmatrix} \right\|}_{\varepsilon_1} + \underbrace{\left\| \begin{pmatrix} Z^{-1}(e_m(k-\delta) - e_s(k)) \\ Z(f_m(k) + f_s(k-\delta)) \end{pmatrix} \right\|}_{\varepsilon_2}. \qquad (13)$$

The transparency deviation index is bounded by a sum of subindexes. Each of these indexes represents the effect on transparency of a particular phenomenon occurring in the implementation of the transmission. The term ε_1 describes the effect on transparency of the communication delay and it does not depend on the scattering implementation of the interconnection. The term ε_2, instead, depends on the scattering-based nature of the channel and it derives from the coding/decoding procedure that is used for going from scattering variables to power variables and *vice versa*. In other words, it represents the price we have to pay in terms of transparency of the communication channel in order to achieve a lossless interconnection. Thus, it proves that transparency and passivity (together with robustness with respect to time delay and intrinsic stability) are conflicting targets as informally stated in [9] for linear telemanipulators.

During the communication over an packet switching networks, it is possible that some packets get lost and that the communication delay is variable. These phenomena can destroy the passivity of the communication channel and they can lead to an unstable behavior of the system [8]. A communication strategy for preserving passivity also in case of packets loss and variable delay has been proposed in [16] and [18]. We will now analyze the effect of this strategy on the transparency of the communication channel. Using the algorithm proposed in [18], when a packet is lost, a zero value is sampled in its place. Thus, let $\mathcal{L}_{ms}$ and $\mathcal{L}_{sm}$ be the set of instants at which a packet is not received in the communication between master and slave and *vice versa*, respectively. The transmission line is described by

$$\begin{cases} s_s^+(k) = (1-\alpha) s_m^-(k-\delta) \\ s_m^+(k) = (1-\beta) s_s^-(k-\delta) \end{cases} \qquad (14)$$

where

$$\alpha = \begin{cases} 1, & k \in \mathcal{L}_{ms} \\ 0, & k \notin \mathcal{L}_{ms} \end{cases}, \qquad \beta = \begin{cases} 1, & k \in \mathcal{L}_{sm} \\ 0, & k \notin \mathcal{L}_{sm}. \end{cases} \qquad (15)$$

Once again, using (1) in (14), by straightforward calculations, it is possible to restate the communication strategy in terms of power variables as

$$\begin{cases} f_s(k) = -f_m(k) + (f_m(k) - f_m(k-\delta)) \\ \qquad\quad + Z^{-1}(e_m(k-\delta) - e_s(k)) - \alpha Z^{-1} s_m^-(k-\delta) \\ e_m(k) = e_s(k) - (e_s(k) - e_s(k-\delta)) \\ \qquad\quad - Z(f_m(k) + f_s(k-\delta)) - \beta s_s^-(k-\delta) \end{cases} \qquad (16)$$

whence, using (11), it is possible to calculate the transparency deviation index that results

$$\varepsilon \leq \varepsilon_1 + \varepsilon_2 + \underbrace{\left\| \begin{Bmatrix} \alpha Z^{-1} s_m^-(k-\delta) \\ \beta s_s^-(k-\delta) \end{Bmatrix} \right\|}_{\varepsilon_3}. \qquad (17)$$

Thus, in case of packet loss, transparency decreases and the contribution to transparency deviation is proportional to the norm of the lost energy packets. This is again linked to the fact that transparency and passivity are conflicting targets. In fact, when packets are lost and the strategy reported in [18] is used, it means that their power content is dissipated. Thus, packet loss introduces dissipation in the communication channel rendering it a strictly passive instead of a lossless system. This increase of passivity leads to a decrease of transparency and the term ε_3 is as more significant as greater is the power associated to the lost packets. In other words, the more the communication channel gets passive, the less it gets transparent.

Several strategies have been developed to recover the packets lost in communication. In case a lost packet is replaced by a packet obtained by interpolation, the transmission is described by

$$\begin{cases} s_s^+(k) = (1-\alpha)s_m^-(k-\delta) + \alpha s_{m\,I}^-(k-\delta) \\ s_m^+(k) = (1-\beta)s_s^-(k-\delta) + \beta s_{sI}^-(k-\delta) \end{cases} \tag{18}$$

where $s_{m\,I}^-$ and s_{sI}^+ are the interpolated packets that replace the master and slave lost packets, respectively. In this case, following the same procedure used to get (17), we have that the transparency deviation index is given by

$$\varepsilon \leq \varepsilon_1 + \varepsilon_2 + \underbrace{\left\| \begin{pmatrix} \alpha Z^{-1}(s_m^-(k-\delta) - s_{m\,I}^-(k-\delta)) \\ \beta(s_s^-(k-\delta) - s_{sI}^-(k-\delta)) \end{pmatrix} \right\|}_{\varepsilon_3}. \tag{19}$$

Now the term related to packets loss depends on the error introduced by the interpolation process. To the best of the authors' knowledge, two passivity preserving interpolation techniques have been developed so far: the one proposed in [13], which replaces a sequence of lost packets with an opportunely weighted linear interpolation of the received packets, and the one reported in [2], where a sequence of lost packets is replaced by a sequence of packets containing the average value of the information carried by the lost ones.

Both schemes require a receiving buffer in order to replace lost packets with the interpolated ones. Consequently, the communication delay increases possibly leading, in general, to an increase of the terms ε_1 and ε_2. Thus, the interpolation reduces the term relative to the packet loss in the transparency deviation index but the price to pay is a possible increase of the terms relative to the delayed communication. Therefore, before enabling any interpolation algorithm, it is necessary to check if the beneficial effect introduced by the interpolation is not overwhelmed by the effect introduced by the increase of delay. This can be done by performing a worst-case analysis (e.g., through the Monte Carlo method) on the value of the signal exchanged and on their variation rate. In fact, loosely speaking, the faster are the dynamics of master and slave sides, the more an increase in communication delay deteriorates transparency of the overall system; in this case, the interpolation should be disabled in order to keep the delay as small as possible. The algorithm proposed in [13] also requires a transmission buffer and this leads to a further increase of communication delay, and consequently, of the terms ε_1 and ε_2. Since no information on the value distribution of the sequence of lost packets is available, the solution of a very simple optimization problem shows that the best way to recover the lost packets is to replace the packets of the lost sequence with a sequence of packets containing the average value of the lost packets. This is exactly what is done in the algorithm proposed in [2].

In summary, the best passivity preserving algorithm for recovering lost packets is that proposed in [2]. It does not introduce any further delay beyond that introduced by the receiving buffer, thus minimizing the effect introduced by the extra delay on the transparency. Furthermore, since the replaced sequence of packets minimizes ε_3, it reduces to the minimum the effect of lost packets on the transparency of the system. Moreover, the fact of preserving passivity does not represent a restriction since the strategy proposed in [2] is the best in terms of transparency.

Now suppose that the communication delay is variable as often happens when using switching packet networks. The communication strategy, in case of variable delay, becomes

$$\begin{cases} s_s^+(k) = s_m^-(k-\delta+n(k)) \\ s_m^+(k) = s_s^-(k-\delta+n(k)) \end{cases} \tag{20}$$

where $n(k) \in \mathbb{Z}$ represents the variability of the delay. We suppose that the delay has the same variability both in the communication between master and slave and *vice versa* in order to keep the notation simple in the computations. The results obtained can be easily extended to the general case. We suppose that the variable delay is an undesired effect and that the communication channel should be characterized by a constant delay δ in both directions. Suppose that the delay is increasing, namely that $n(k+1) < n(k)$ and that the packets $s_s^+(k) = s_m^-(k-\delta+n(k))$ and $s_m^+(k) = s_s^-(k-\delta+n(k))$ have just been received; we then have

$$\begin{cases} s_s^+(k+i) = 0, \qquad i = 1, \ldots, [n(k+1)-n(k)-1] \\ s_s^+(k+(n(k+1)-n(k))) = s_m^-(k-\delta+n(k)+1) \end{cases}$$
$$\begin{cases} s_m^+(k+i) = 0, \qquad i = 1, \ldots, [n(k+1)-n(k)-1] \\ s_m^+(k+(n(k+1)-n(k))) = s_s^-(k-\delta+n(k)+1) \end{cases} \tag{21}$$

where, when a packet is late, it is replaced with 0 in order to preserve passivity as proven in [18]. Assuming that there is no packet loss to keep the notation simple and proceeding in the same way as done for computing the previous subindexes, we have that

$$\varepsilon \leq \varepsilon_1 + \varepsilon_2 + \varepsilon_4 \tag{22}$$

where (23) shown at the bottom of the page.

The effect on transparency of an increase of delay is twofold: for $n(k+1)-n(k)-1$ samples, it brings the same effect brought by a packet loss since, because of the increasing delay, the expected packet is not delivered on time and it is replaced by 0. Furthermore, there is a second effect due to the fact that when the packet is finally delivered, it is not the packet that is expected at that instant. Unlike for the case of packets loss, it is not possible to replace the "holes" due to the increase of delay by interpolation since the transmitted packets finally arrive. If we filled the holes with new packets, we would introduce extra energy

$$\varepsilon_4(k+i) = \begin{cases} \left\| \begin{pmatrix} Z^{-1}s_m^-(k-\delta+n(k)+i) \\ s_s^-(k-\delta+n(k)+i) \end{pmatrix} \right\| i = 1, \ldots, [n(k+1)-n(k)-1] \\ \left\| \begin{pmatrix} Z^{-1}(s_m^-(k-\delta+n(k)+1) - s_m^-(k-\delta+n(k)+n(k+1)-n(k)) \\ (s_s^-(k-\delta+n(k)+1) - s_s^-(k-\delta+n(k)+n(k+1)-n(k)) \end{pmatrix} \right\| i = [n(k+1)-n(k)]. \end{cases} \tag{23}$$

into the system leading to a nonpassive communication channel. Thus, while preserving passivity is not a constraint for the recovery process for lost packets, it is a constraint for the compensation of the effects due to variable delay. Now suppose that the communication delay is decreasing, namely that $n(k) < n(k+1)$. Very long delays (e.g., using retransmission techniques) and wave distortion (due to the fact that packets does not arrive in the correct order) have to be avoided because of their deleterious effect on performances. One of the most used strategy for avoiding these phenomena is the Use Freshest Sample (UFS) strategy. A time stamp is attached to each transmitted packet and if a packet older than the last received packet arrives, it is simply discarded. This technique preserves passivity as shown in [7]. Thus, the effect of a decrease of delay on the transparency is the same as that given by a packet loss.

In summary, the framework for the analysis of transparency introduced in Section III allowed analyzing the scattering-based switching packets communication strategy used for the interconnection of master and slave sides in port-Hamiltonian-based telemanipulation. It has been possible to recognize various factors affecting transparency and to formally prove that transparency and passivity are conflicting targets. The transparency deviation index of the communication channel is bounded by the sum of four terms: ε_1 that takes into account the communication delay, ε_2 that considers the scattering coding/decoding procedure. The possible decrease in transparency due to the scattering-based implementation is the price to pay in order to achieve a lossless transmission. The term ε_3 encodes the effect of packets loss and it can be optimally minimized in a passive way by replacing the lost packets by interpolated packets. Finally, the term ε_4 encodes the effects due to the variability of the time delay; these are the most critical effects since they cannot be compensated without affecting the passivity of the communication channel.

Notice that the values of the subindexes depend on the efforts and flows exchanged between master and slave sides, namely on the dynamics of the overall telemanipulation system. Nevertheless, their presence and the possibility of mitigating them is independent of the overall dynamics. Thus, it is possible to associate to each phenomenon that degrades transparency an index that describes it and to study how to mitigate their effect while preserving passivity of the system.

In conclusion, the variable delay is a phenomenon more dangerous than packets loss for the transparency of the interconnection between master and slave sides. In fact, while it is not possible to recover the transparency deviation effect due to variable delay, it is possible to passively minimize the effects of packet loss through the interpolation algorithm proposed in [2].

The transparency analysis provided in this section can also be applied to communication channels that are used to transmit any dual information (e.g., parameters of the impedance controllers, [16]). The behavior of these channels is very similar to that reported in (11) and the transparency analysis follows very similar steps to that presented in this section.

V. Simulations

The aim of this section is to provide some simulations in order to validate the results obtained.

We consider a simple 1 DOF telemanipulator where master and slave are simple masses of 1 kg, which can be modeled as port-Hamiltonian systems. The port-Hamiltonian impedance controllers are simple potential difference (PD), physically equivalent to the parallel of a spring with stiffness $K = 1$ N/m and a damper with dissipation coefficient $b = 1$ N·s/m, passively discretized and interconnected to the robots using the techniques proposed in [18]. Master and slave sides are

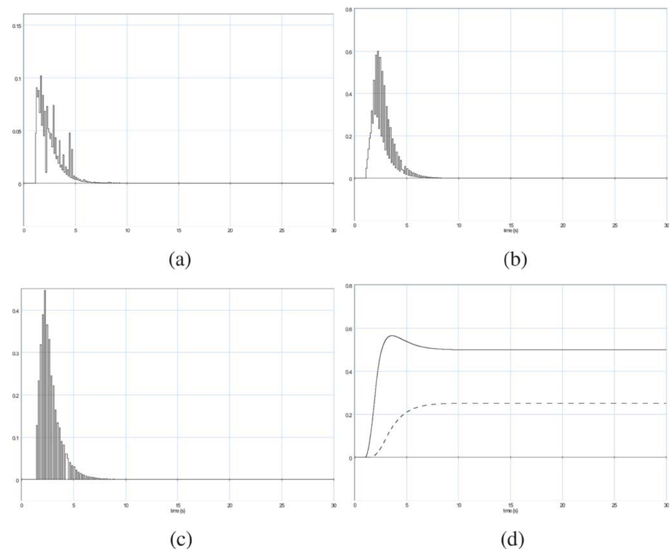

Fig. 2. Effect on transparency of loss of packets in the communication. (a) ε_1. (b) ε_2. (c)ε_3. (d) Position of master (solid) and slave (dashed).

interconnected through a scattering-based switching packet communication channel with nominal delay $\delta = 0.2$ s. We simulated the effect of an impulsive force applied by the user. In this way, due to the virtual mechanical coupling implemented by the controllers via the communication channel, we have an exchange of energy both between master and slave and slave and master. Furthermore, the effect of the nontransparency of the scattering-based communication channel can be directly seen on the position error that takes place between master and slave.

In the first simulation, we implemented a packet loss, with loss rate of 50% in both senses of communication. The terms relative to transparency deviation and the position of master and slave are reported in Fig. 2.

The steady-state position mismatch between master and slave is due to the strategy used for handling lost packets. Replacing a lost packet or a late packet with a null packet allows to preserve passivity of the communication channel, and consequently, to avoid destabilizing effects. Unfortunately, this strategy implies that the content of the lost packets is dissipated [18] and that, therefore, some of the energy that should have been delivered for performing a tracking task is lost. Consequently, the slave can only partially track the position of the master. An algorithm for passively compensating this steady-state position error can be found in [15].

We can see that all the transparency subindexes tends to zero. This is due to the fact that after a certain transient, the system stops, and therefore, zero efforts and zero flows are exchanged along the communication channel that, therefore, appears completely transparent. During the motion, the transparency, deviation terms are different form zero meaning that the communication channel is not transparent. In particular, ε_3 exhibits peaks that correspond to the packets lost in the communication. A nontransparent communication channel leads to a nontransparent telemanipulation system as can be noticed by the positions of master and slave that are quite different.

In Fig. 3, the behavior of the communication channel is reported when the interpolation algorithm proposed in [2] is enabled. We can see that the term ε_1 slightly increases because of the increase of delay induced by the receiving buffer. Nevertheless, this slight increase is greatly repaid by the decrease of the term ε_3 because of the optimal recovery of the sequences of lost packets. The overall decrease of

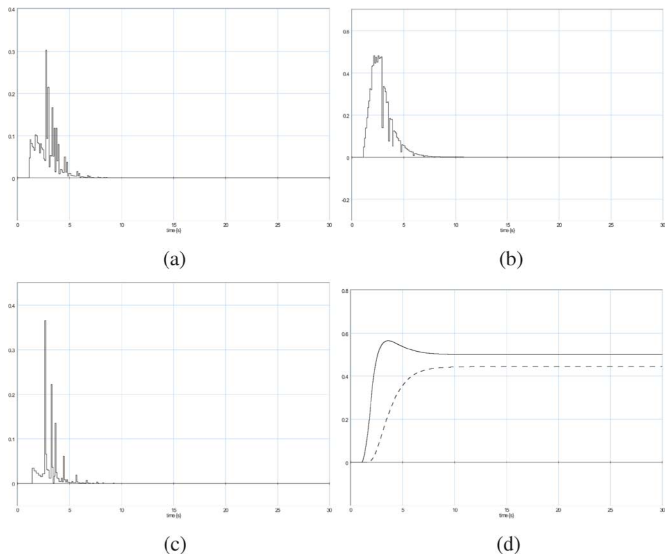

Fig. 3. Effect on transparency of loss of packets in the communication when interpolation is enabled. (a) ε_1. (b)ε_2. (c) ε_3. (d) Position of master (solid) and slave (dashed).

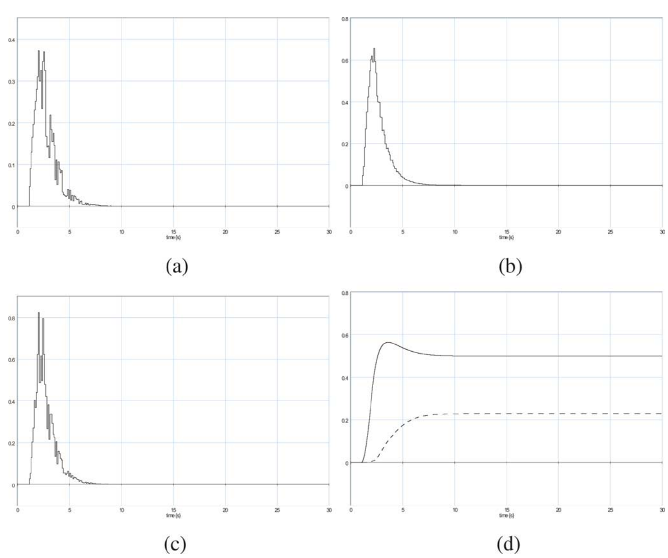

Fig. 4. Effect on transparency of variable delay in the communication.(a) ε_1. (b) ε_2. (c) ε_4. (d) Position of master (solid) and slave (dashed).

transparency deviation of the communication channel can be observed in an increase of performances in the positioning task; in fact, now, the position of the slave is closer to that of the master.

In the last simulation, we implement a variable communication delay where the UFS strategy (see Section IV) is adopted. The simulation results are reported in Fig. 4. We can see that both ε_1 and ε_2 increase because of the variability of the delay. Furthermore, the term ε_4, which encodes the effect of variable delay, is the most significant transparency deviation term. The effect of variable delay is the most deleterious since no action can be taken to compensate it without affecting the passivity of the communication. The performances of the telemanipulation system are quite bad, as it can be noticed by looking at the positions of master and slave. Nevertheless, the system keeps on being stable because the communication channel keeps on being passive as proven in [18].

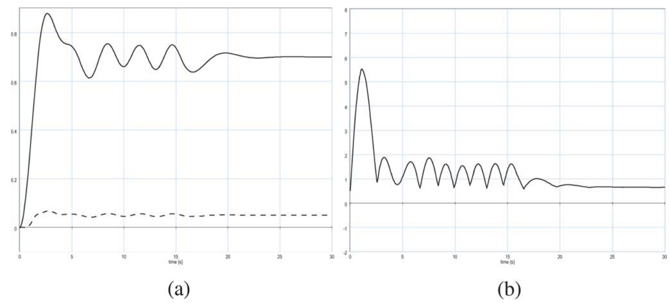

Fig. 5. Transparency of the overall telemanipulation system in case of contact with a soft environment. (a) Position of master (solid) and slave (dashed). (b) $\varepsilon(t)$.

In all the simulations, the transparency deviation index goes to zero despite of the steady-state position error due to the unreliabilities of the communication. This is due to the fact that we have performed a transparency analysis of the communication channel and *not* of the overall teleoperation system. As reported in Section IV, the behavior of the transmission line is degenerate and it does not depend on configuration information. Nevertheless, the presence of the position error is an indicator of the effect of the nontransparency of the communication channel on the overall telemanipulation system.

In the next simulation, we consider the transparency of the overall telemanipulation system in case of contact with a soft environment. We consider the same 1 DOF telemanipulator that we used for the previous simulation but now we are considering a constant communication delay of 0.5 s. The slave is in contact with a soft viscoelastic environment that is modeled as the parallel of a spring with stiffness $k_e = 10$ N/m and of a damper with damping coefficient $b_e = 1$ N·s/m. The user first applies a sinusoidal force profile keeping the slave in contact with the environment, as if he/she were probing the environment by the slave, and after 15 s, a constant force is applied. The positions of master and slave robots can be seen in Fig. 5(a). We can see that, at steady state, the force applied by the user is equilibrated by the force fed back from the slave side. The position error at steady state takes place because in passivity-based telemanipulation system, the force feedback is implemented through an elastic coupling between master and slave; for more information, see [11].

Both master and slave sides can be modeled as port-Hamiltonian systems with $\mathcal{X} = \mathbb{R}^2 \ni (x_i, p_i)$, $i = s, m$, where x_i and p_i indicate the state of the virtual spring in the impedance controller and the momentum of the mass, respectively. Let us denote with q_s the position of the slave. Let us indicate with (e_E, f_E) and (e_H, f_H) the power ports through which the telemanipulation system interacts with the environment and with the user, respectively.

If we indicate with $w_E(t) = (e_E(t), f_E(t), (x_s(t), p_s(t))^T)$ the port outcome at the slave side, it can be easily shown that the port behavior at the environment port is given by

$$\Delta^{\mathcal{E}}(t, pr^{(1)} w_E(t)) = \begin{pmatrix} \dot{e}_E(t) + k_e f_E(t) + b_e \dot{f}_E \\ \int_0^t p_s(\tau) d\tau = q_s(t) \end{pmatrix}. \tag{24}$$

The first component represents the dynamic behavior related to the exchange of energy while the second component represents a constraint that has to be satisfied by the state of the system that interacts with the environment. If we indicate the port outcome of the master side as $w_H(t) = (e_H(t), f_H(t), (x_m(t), p_m(t))^T)$, we can compute the transparency deviation index, which is plotted in Fig. 5(b), as

$$\varepsilon(t) = \|\Delta^{\mathcal{E}}(t, pr^{(1)} w_H(t))\|. \tag{25}$$

We can see that as long as the user is probing the environment, the transparency deviation index is greater than zero and variable, meaning that the feeling perceived by the user is different from the dynamic contact behavior at the slave side. At steady state, we have that the transparency deviation index is different from zero but constant. This means that, despite of the fact that there is no energy exchange and the system is in equilibrium, the telemanipulator is not completely transparent because the position of the master is different from that of the slave.

VI. Conclusion and Future Work

In this paper, we have illustrated how it is possible to evaluate transparency for port-Hamiltonian-based bilateral telemanipulation systems. This is done by using the concept of port behavior and behavioral deviation. An index has been proposed in order to evaluate transparency of the overall or of components of a telemanipulation system. The proposed framework has been exploited to study transparency of scattering-based switching packet communication channels. We have formally shown that transparency and passivity are conflicting targets and we have illustrated the effects of loss of packets and variable delay on the transparency of the communication channel.

Future work will deal with the development of passivity preserving adaptive techniques in order to shape both master and slave sides to improve transparency of the overall telemanipulation system. We have currently developed an algorithm for passively changing the parameters of the port-Hamiltonian impedance controllers [16]. We believe that the controller should be shaped depending on the different use cases. We are classifying classes of human port behavior (e.g., slow interaction, fast free motion, etc.), and for each of these classes, we are making a worst-case analysis using the transparency deviation index proposed in the paper (i.e., we take the maximum of the transparency deviation over time) in order to identify the optimal controller parameters. Since we are restricting the port behavior to a given scenario, the measure that we get should not be too conservative. After this analysis, we will have a set of controllers, each of which maximizes transparency for a given use case of the teleoperator. An efficient, passivity preserving, way to switch between the controllers has to be developed.

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