Analytical Study of Perceptual and Motor Transparency in Bilateral Teleoperation

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***Abstract*—In bilateral teleoperation, a human operator manipulates a remote environment through a pair of master and slave robots. The transparency quantifies the fidelity of the teleoperation system, and is typically defined as the ability to accurately display remote environment properties to the operator. We propose a novel multidimensional measure of transparency which takes into account the human operator and consists of three components: 1) perceptual transparency, which quantifies human perception of the remote environment, 2) local motor transparency, which quantifies how far is the movement of the human operator from ideal, and 3) remote motor transparency, which describes how far is the movement of the remote device from ideal. We suggest that for many practical applications, the goal of the transparency optimization is to maintain perceptual and remote motor transparency while sacrificing local motor transparency, and that it is plausible to take advantage of the gap between perception and action in the operators sensorimotor system. We prove analytically that for a teleoperation channel with a position and force scaling and a constant transmission delay, in a palpation and perception of stiffness task, it is possible to find gains that ensure perfect perceptual and remote motor transparency while maintaining stability. We also show that stability depends on the operator that maintain sufficient arm impedance relative to environment impedance and delay.**

***Index Terms*—Delay effects, haptics, haptic interfaces, human factors, human perception, physical human–robot interaction, telerobotics.**

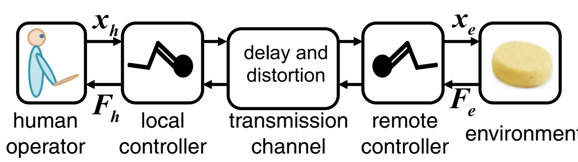

Fig. 1. Schematic teleoperation system. The human operator acts through a local controller, a channel, and a remote controller on the remote environment with delayed and distorted feedback.

I. Introduction

In bilateral teleoperation, human operators interact with a remote environment by moving a local master robot that controls the motion of a remote slave, and feel the forces reflected from the slave to the master (see Fig. 1). The quality of interaction is affected by the teleoperation channel properties, which have been analyzed extensively. However, until recently, the influence of human operators and their perceptual and motor capabilities has been largely overlooked. We aim to develop a framework that exploits the knowledge of perceptual and motor capabilities and limitations of the human operator to generate perceptually transparent and functional teleoperation systems. In such systems, our goal is for the operator's intentions to be accurately executed in the remote environment, and for the operator to perceive the environment accurately. The primary application of this study is telemedicine, such as remote rehabilitation [1], [2] and telesurgery [3], [4], but our hope is that a broader range of applications will eventually benefit from the enhancements in telerobotics and telepresence technologies, e.g., handling hazardous materials from safe distance, performing space vessels maintenance tasks [5]–[7], and adding a personal touch to standard telecommunications [8], [9].

Stability and transparency are the two important aspects of teleoperation systems addressed extensively in the literature [10]–[21]. Here, our main interest is in transparency, and we assume that any general manipulation that we suggest to obtain transparency is done within the constraints set by the stability demands, and analyze stability for the simplified linear case in Section V. Transparency is a measure of teleoperation system fidelity. An ideally transparent system is the identity channel, in which equal force and velocity are transmitted between the two sides. The human operator is an inherent part of the teleoperation system, and therefore, we suggest that a teleoperation design based on the optimization of transparency that includes the operator may improve the performance of the system when compared with the optimization of transparency of the isolated mechanical system. To address this challenge, we suggest a novel multidimensional measure of transparency which includes three components (see Fig. 2):

i) *Perceptual transparency*: The human operator cannot distinguish between the system and an identity channel.
ii) *Local motor transparency*: The movement of the operator (position and force trajectories) does not change when the teleoperation system is replaced by an identity channel.
iii) *Remote motor transparency*: The movement of the remote robot (position and force trajectories) does not change when the teleoperation system is replaced by an identity channel.

Manuscript received April 30, 2013; accepted August 05, 2013. Date of publication November 7, 2013; date of current version November 26, 2013. This research was supported by grant no. 2003021 from the United States–Israel Binational Science Foundation (BSF), Jerusalem, Israel. The work of I. Nisky was supported by the Kreitman and Clore Scholarships, the Weizmann Institute National Program for Promoting Women in Science, and by the Marie Curie International Outgoing Fellowship. This paper was recommended by Associate Editor D. Abbink of the former IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans (2012 Impact Factor: 2.183).

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Digital Object Identifier 10.1109/TSMC.2013.2284487

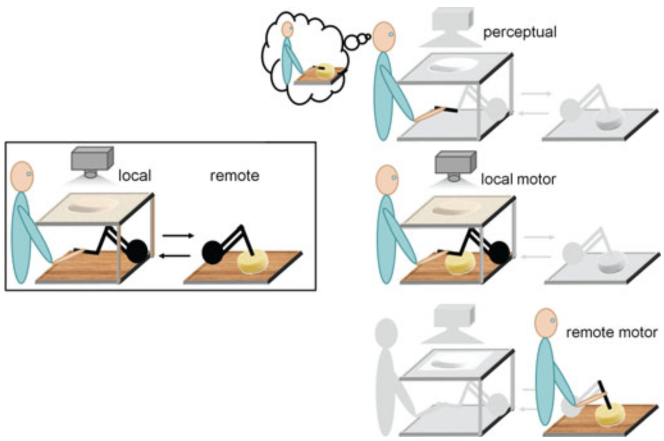

Fig. 2. Three components of transparency: the actual teleoperation system (left) can be perceptually (upper right), locally motor (middle right), and remotely motor (lower right) transparent.

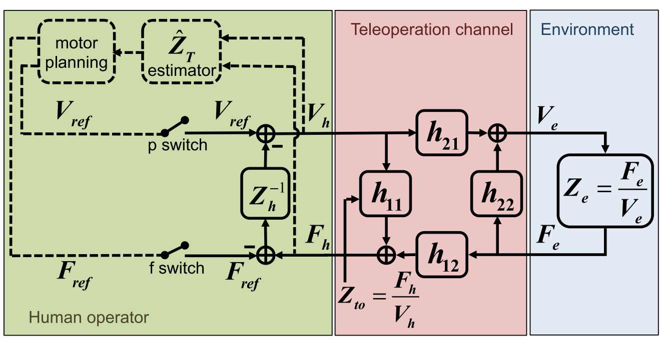

Fig. 3. Example of two-port representation of a teleoperation system, and block diagram of one possible representation of human operator and environment. Z_{e} and Z_{h} are the environment and human operator impedances, respectively, and Z_{to} is the impedance presented to the operator. When the p-switch is closed, the system is under position control of the human operator, and when the f-switch is closed, it is under force control of the human operator. The dashed lines and boxes are one possible representation of the processes inside the human operator motor control system. We keep this representation as general as possible to keep the perceptuomotor transparency framework general with respect to the detailed structure of the human motor control system. In Section VI, we address several possible levels of specification for this structure.

In Fig. 3, a block diagram of one possible representation of a human operator, teleoperation channel, and environment is depicted. The details of the teleoperation channel are explained in Section II, but at this point, we would like to focus on the human operator and environment. The human operator is represented by an impedance, Z_{h}, and by movement and force signals, V_{h} and F_{h}, respectively. The dashed lines depict a hypothetical representation in the human operators' sensorimotor system that include a perceived impedance block, $\hat{Z}_T$, and a motor planning block from which reference trajectories V_{ref} and F_{ref} can be extracted. The perceived impedance block $\hat{Z}_T$ is distinct from Z_{to}, the impedance that is presented to the operator at the local side. At the remote side, the remote manipulators movements and forces are V_{e} and F_{e}, respectively, and the impedance of the environment is Z_{e}. In this schematic representation, ideal *perceptual transparency* amounts to $\hat{Z}_T = Z_{\mathrm{e}}$, *local motor transparency* amounts to $(V_{\mathrm{h}}, F_{\mathrm{h}}) = (V_{\mathrm{ref}}, F_{\mathrm{ref}})$, and *remote motor transparency* amounts to $(V_{\mathrm{e}}, F_{\mathrm{e}}) = (V_{\mathrm{ref}}, F_{\mathrm{ref}})$.

From a practical point of view, the motor task is often defined in the remote environment, whereas the most realistic perception must be rendered in the local site. In this sense, local motor transparency, i.e., maintaining the motion of the operator in close matching with the desired remote motion, is relatively unimportant. We suggest that for a nonideal teleoperation channel, it is possible and beneficial to obtain i) perceptually transparent teleoperation and ii) remote motor transparency without iii) local motor transparency. In practice, perceptual and remote motor transparencies are simultaneously attainable by changing either the local or remote controllers, and by training of the human operator.

Let us further explain the components of our suggested transparency measure by means of an example from a possible application: a remote surgical procedure that requires to cut a soft connective tissue while avoiding damage to the stiffer vessels and muscle tissue. In this scenario, there are two actions (probing and cutting) and two perceptions (soft and stiff tissue). The surgeon acts in a local virtual environment, but the actual procedure is done on a remote patient via a teleoperation system. As a result of a nontransparent system, three potential problems that correspond to the three components of transparency can arise: i) the surgeon can misperceive soft connective tissue as stiff muscle/vessel tissue; ii) the surgeon can virtually damage the local model of the tissue when she wishes to probe the tissue; iii) the surgeon can actually damage the real remote tissue when she intends to probe it.

There might be scenarios in which these three problems overlap. For example, if the surgeon damages the muscle because of procedural judgment error that result from misperception. To optimize system design, it is important to identify which of the errors was a result of the teleoperation: here, the perceptual transparency error lead to an incorrect estimation of the impedance of the environment (the muscle) which lead to an incorrect desired movement that was accurately executed in terms of remote motor transparency. Analyzing and treating each of the errors separately allows to take advantage of the gap between perception and action that exists in the motor system of the human operator [22], [23], and particularly, the gap that we found in the effect of delay on perception and action [24], [25].

In a preliminary version of this study [26], we defined these three components of transparency mathematically, and derived the ideal conditions for transparency. We also demonstrated the feasibility of our framework by means of simulation of virtual teleoperation. Then, we employed our framework in an experimental study of virtual teleoperated needle insertion [25]. In this paper, we present for the first time a complete analytical study of this framework. We provide an analytical motivation for our approach based on our experimental studies of human perception and action in delayed environments. We refine the previously presented mathematical definitions of perceptual and motor transparency, and repeat the derivation of ideal conditions for transparency for completeness. We prove that ideally, it is possible to achieve perceptual and remote motor transparency for a general linear teleoperation system (Proposition 1), but the conditions are not easy to satisfy. In addition, we prove that under simplifying assumptions of linearity and constancy of transmission delays and gains in the teleoperation channel, it is possible to achieve perceptual and remote motor transparency in a stiffness probing task by setting the appropriate values to velocity and force gains (Proposition 2), and derive the conditions for stability of such system (Proposition 3).

The remainder of the paper is organized as follows: in Section II, we review preliminaries in teleoperation and human perception and action in delayed environments. We define our transparency measure in Section III, and analyze it analytically for a general linear system in Section IV. We prove that it is possible to design stable and transparent teleoperation for a simple architecture in a one-dimensional (1-D) slicing task in Section V, and conclude the paper with a discussion in Section VI and conclusions in Section VII.

II. Preliminaries

The teleoperation systems are typically described as two-port networks that are represented by a hybrid parameters model of their lumped LTI dynamics [10], [12], [13]. In this framework, one of the possible channel descriptions is

$$\begin{bmatrix} F_{\mathrm{h}}(s) \\ V_{\mathrm{e}}(s) \end{bmatrix} = H(s) \begin{bmatrix} V_{\mathrm{h}}(s) \\ F_{\mathrm{e}}(s) \end{bmatrix} = \begin{bmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{bmatrix} \begin{bmatrix} V_{\mathrm{h}}(s) \\ F_{\mathrm{e}}(s) \end{bmatrix}$$

$$= \begin{bmatrix} Z_{\mathrm{in}}(s)\Big|_{F_{\mathrm{e}}(s)=0} & G_{\mathrm{F}}(s)\Big|_{V_{\mathrm{h}}(s)=0} \\ G_{\mathrm{V}}(s)\Big|_{F_{\mathrm{e}}(s)=0} & Z_{\mathrm{out}}^{-1}(s)\Big|_{V_{\mathrm{h}}(s)=0} \end{bmatrix} \begin{bmatrix} V_{\mathrm{h}}(s) \\ F_{\mathrm{e}}(s) \end{bmatrix} \quad (1)$$

where $F_{\mathrm{h}}(s)$, $F_{\mathrm{e}}(s)$ are the forces and $V_{\mathrm{h}}(s)$, $V_{\mathrm{e}}(s)$ are the velocities for the local (human) and remote (environment) sides, respectively, and $H(s)$ is called a hybrid matrix. The physical interpretation of the components of this hybrid matrix is: Z_{in} and Z_{out} are input and output impedances, respectively; $G_{\mathrm{V}}(s)$ is velocity scaling in transmission between the local and the remote side; and $G_{\mathrm{F}}(s)$ is force scaling in transmission between the remote and the local side (see Fig. 3 for a block diagram of this representation).

In the last two decades, various definitions and conditions for transparency have been presented. These include perfect correspondence of position and force signals [14], exact transmission of impedance or admittance [13], [16], or frequency-dependent transfer functions [21]. Some studies define a physical equivalent for the channel, e.g., infinitely stiff weightless connection [15], or light and stiff virtual tool [11], [17], [20]. The common feature among these approaches is to utilize network functions formulation to address transparency. Importantly, under these definitions, ideal transparency conditions are unattainable [27], particularly in the presence of transmission delays [17]. For the case of the four-channel teleoperation architecture [13], [16], transparency is achievable under ideal conditions, but there is a stability–transparency tradeoff.

In some studies, the human operator was taken into account. This was achieved by considering force perception thresholds [10], just noticeable difference for mechanical properties and time delay [27], [28], or weighted relative change in environment impedance [28], [29]. Recently, in parallel to our work [26], more studies evaluate teleoperation systems in terms of human perception and task performance [30]–[33]. However, currently, there is no systematic and consistent definition for the transparency of teleoperation systems that take into account the human operator as part of the overall system.

A prominent and unavoidable characteristic of the bilateral teleoperation systems is the delay between movements of the operator and force feedback. We have extensively studied the influence of the delay between position and force on the perception of mechanical stiffness of spring-like force fields [34]–[36], and on action during contact with such force fields [24]. A spring-like force field is a one-sided linear spring, i.e., a compression spring, in which an elastic force field is applied whenever the boundary of the field is crossed, namely, when the human operator created contact with the spring. We found that subjects overestimate stiffness when force lags position [34], but when the hand of the subjects remained in continuous contact with the elastic force field, they underestimated the delayed stiffness [35]. Moreover, we found a proximal–distal gradient in the amount of underestimation of delayed stiffness in the transition between probing with shoulder, elbow, and wrist joints [36]. Interestingly, cognitive and motor representations of the world around us are not always mutually consistent [22], [23]. We found such inconsistencies between declarative and motor-related perception of linear stiffness [24] and of nonlinear needle-insertion-like force field [25].

In the remainder of the paper, we use our experimentally confirmed model for perception of stiffness [35], [36]. We concentrate on the linear case, and assume wrist movements in continuous contact with the elastic spring. In this case, the perceived stiffness, $\hat{K}_T$, is estimated as the slope of regression of force over position sampled data, namely

$$\hat{K}_T = (\underline{\mathbf{x}}_{\mathbf{h}}{}^T \underline{\mathbf{x}}_{\mathbf{h}})^{-1} \underline{\mathbf{x}}_{\mathbf{h}}{}^T \underline{\mathbf{f}}_{\mathbf{h}} \quad (2)$$

where $\underline{\mathbf{x}}_{\mathbf{h}}$ and $\underline{\mathbf{f}}_{\mathbf{h}}$ are the sampled position and force vectors, respectively.

III. Perceptuomotor Transparency

We suggest a new transparency measure, and set the goal of achieving transparency for the coupled system: human operator and teleoperation channel. The classical transparency analysis quantifies the distance from an ideal system by observing the transfer functions in the Laplace or frequency domain. This kind of analysis can be appropriate for the effect of teleoperation on action in cases where the user and teleoperation channel can be approximated as linear systems, but it does not fully capture the nonlinear effects on perception, or on action in the general case. In particular, the gaps are evident in the case of teleoperation with transmission delay.

Let us examine a simple example of teleoperation with pure delay. Based on our experimental results described in the previous section, it is evident that as far as the human operator is concerned, a pure delayed channel is not transparent. In these experiments, the subjects were in contact with an elastic force field, $f_{\mathrm{e}}(t) = Kx_{\mathrm{e}}(t)$, and therefore, $Z_{\mathrm{e}}(s) = F_{\mathrm{e}}(s)/V_{\mathrm{e}}(s) = K/s$. The channel was a pure delay ΔT, and thus, $x_{\mathrm{e}}(t) = x_{\mathrm{h}}(t - \Delta T)$, $f_{\mathrm{h}}(t) = f_{\mathrm{e}}(t - \Delta T)$, and the impedance that was presented to the operator was $Z_{\mathrm{to}}(s) =$

$F_{\mathrm{h}}(s)/V_{\mathrm{h}}(s) = e^{-s2\Delta T}K/s$, where $2\Delta T$ is the round trip delay of 50 ms. The ratio $Z_{\mathrm{to}}(s)/Z_{\mathrm{e}}(s) = e^{-s2\Delta T}$ is almost ideally transparent with respect to the network functions framework: it is transparent in magnitude, and includes a linear phase shift. In many studies, the analysis of transparency is performed with respect to the magnitudes of transfer functions [21], [29], [37], [38], and the analysis of stability takes into account the phase. In some studies, delay is taken into account as phase shift, or using the Pade rational approximation of delay [19]. In general, this nearly ideal transparency transfer function is in contradiction with our experimental observation that a teleoperation channel consisting of a pure delay is not transparent in terms of human perception and action. Here, we suggest a novel approach to quantify these effects.

A. Motor Transparency Error

The following definitions refer to both local and remote transparencies. Consider the mixed configuration/force vector $\mathbf{q}(t)$ which consists of the position, $\mathbf{x}(t)$, orientation, $\boldsymbol{\theta}(t)$, force $\mathbf{f}(t)$, and torque $\boldsymbol{\tau}(t)$

$$\mathbf{q}(t) = [\,\mathbf{f}(t) \quad \boldsymbol{\theta}(t) \quad \mathbf{f}(t) \quad \boldsymbol{\tau}(t)\,]. \tag{3}$$

For a specific temporal window and sampling rate, we observe the following mixed configuration/force matrix:

$$\underline{\mathbf{q}} = [\,\mathbf{q}(t_1)^T \quad \cdots \quad \mathbf{q}(t_N)\,]^T \tag{4}$$

where the $\bullet^T$ superscript is the transpose of a matrix. Using this notation, for a specific task, we can define a reference trajectory in the configuration/force space, $\underline{\mathbf{q}}_{\mathbf{ref}}$. Ideally, we would like to use the planned trajectory of the user as a reference trajectory (see dashed lines in Fig. 3); however, because we do not have access to this trajectory, we assume that the user aims for a trajectory that optimizes the performance according to the requirements of the task. This trajectory can be general, and define path only, or specific, and define exact position and interaction forces as a function of time. There might be requirements such that this reference trajectory will be feasible; for example, if the environment couples position and force (e.g., linear spring), the reference trajectory must be in accordance with this coupling. To keep the analysis general, in our definitions, we do not consider how such a trajectory should be determined, or whether it is represented anywhere in the human motor system.

We define the motor transparency error (MTE) based on the distance between the reference trajectory matrix, $\underline{\mathbf{q}}_{\mathbf{ref}}$, and the actual (local or remote) trajectory matrix $\underline{\mathbf{q}}_{\mathbf{T}}$

$$\mathrm{MTE} = (\|\underline{\mathbf{q}}_{\mathbf{T}} - \underline{\mathbf{q}}_{\mathbf{ref}}\|_{\mathbf{W}})/C \tag{5}$$

where $\|\underline{\mathbf{q}}\|_{\mathbf{W}}$ is a weighted norm, such as the weighted quadratic norm $\mathrm{Tr}(\underline{\mathbf{q}}\mathbf{W}\underline{\mathbf{q}}^T)$, $\mathbf{W}$ is a weighting matrix that takes care of the units conversion, physical quantities conversion, and relative weighting between the different components of the configuration/force vector, and C is a complexity measure of the task, such as the length or duration of the movement. The *MTE* can be calculated based on the entire trajectory, or at specific time instances.

Using this definition, the local or remote motor transparency errors (MTE_L or MTE_R, respectively) are defined by assigning the appropriate mixed configuration/force matrix values into (5). For MTE_L, these are the values of the local side of the system, $\underline{\mathbf{q}}_{\mathbf{hT}}$, and for MTE_R, the values of the remote side, $\underline{\mathbf{q}}_{\mathbf{eT}}$.

B. Perceptual Transparency Error

The human perception of mechanical properties follows Weber's law [39]. Therefore, we use a relative measure [27] and define the perceptual transparency error (PTE) as

$$\mathrm{PTE} = |(\hat{Z}_T - \hat{Z}_I)/\hat{Z}_I| \tag{6}$$

where $\hat{Z}_T$ is the estimation of the perceived impedance through the teleoperation channel, and $\hat{Z}_I$ is the perceived impedance through an ideal channel. This definition of perceptual transparency error is very general, since it does not include a specific definition for the estimation of perceived impedance. For example, it is identical to one of the classical definitions of transparency [13], [16], if we substitute $\hat{Z}_T = Z_{\mathrm{to}}(s)$ and $\hat{Z}_I = Z_{\mathrm{e}}(s)$.

In our more specific definition of perceptual transparency error, we concentrate on the perception of stiffness, and define *PTE* as

$$\mathrm{PTE} = |(\hat{K}_T - \hat{K}_I)/\hat{K}_I| \tag{7}$$

where $\hat{K}_I$ and $\hat{K}_T$ are the estimation of the perceived stiffness through the identity and the general channels, respectively. We chose to concentrate on stiffness because it is the dominant mechanical property in the bandwidth of natural movements [28]. Nevertheless, a similar definition can be used for other mechanical properties that might be important for different teleoperation applications.

IV. Optimization of Transparency

We can formulate our goal to minimize the perceptual and remote motor transparency error as follows:

$$H = \underset{h_{ij};\, i=1,2;\, j=1,2}{\operatorname{argmin}} \{w_{\mathrm{P}}\mathrm{PTE} + w_{\mathrm{MR}}\mathrm{MTE}_R\} \tag{8}$$

where the $\bullet_R$ subscript refers to remote, and w_{P} and w_{MR} are the weights for perceptual and remote motor transparency errors, respectively. This optimization should be performed such that human factor constraints are met at the local side, e.g., limits of comfortable and dexterous workspace, or excessive movements that might cause fatigue.

A. Ideal Transparency

Using the notation that we introduced in Section II, Fig. 3, and a few algebraic manipulations on (1), we write the impedance observed by the human operator as

$$Z_{\mathrm{to}}(s) = h_{11}(s) + h_{12}(s)h_{21}(s)(1 - Z_{\mathrm{e}}(s)h_{22}(s))^{-1}Z_{\mathrm{e}}(s). \tag{9}$$

For simplicity, in the remainder of the paper, we consider 1-D movements and forces (no torques), such that $\mathbf{q}(t) = [\,x(t) \quad f(t)\,]$, with its Laplace transform $\mathbf{Q}(s) =$

TABLE I
IDEAL CONDITIONS FOR MOTOR TRANSPARENCY

Local	Remote
User position control	
$Z_\mathrm{h}(s) \to \infty$ $Z_\mathrm{to}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s)$	$\frac{h_{21}(s)}{1-h_{22}(s)Z_\mathrm{e}(s)} \cdot \frac{Z_\mathrm{h}(s)}{Z_\mathrm{h}(s)+Z_\mathrm{to}(s)} = 1$ $Z_\mathrm{e}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s)$
User force control	
$Z_\mathrm{h}(s) \to 0$ $Z_\mathrm{to}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s)$	$\frac{h_{21}(s)}{1-h_{22}(s)Z_\mathrm{e}(s)} \cdot \frac{Z_\mathrm{e}(s)}{Z_\mathrm{h}(s)+Z_\mathrm{to}(s)} = 1$ $Z_\mathrm{e}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s)$

Note that these conditions were derived for the case of teleoperator position–force architecture, and the position and force control defined in the table relate to the human operator control choice. The ideal conditions for other architectures, that include the most general four-channels architecture, can be derived similarly, but are left out of the scope of this paper for clarity and flow of paper.

$[\,X(s) \quad F(s)\,]$. Under these assumptions, perfect local motor transparency (5) is satisfied for $\mathbf{q_T}(t) = \mathbf{q_h}(t) = \mathbf{q_{ref}}(t)$, and thus for $\mathbf{Q_h}(s) = \mathbf{Q_{ref}}(s)$.

When deriving the conditions for motor transparency, we consider two possible control strategies of the human operator: position and force control, and one possible teleoperator control architecture: position–force. Generally, it is possible to follow the same method and derive the ideal conditions for transparency for any teleoperation architecture. We chose to focus on the simplistic position–force architecture because we ground our theory in our human studies [24], [34]–[36] that were obtained using this architecture. For the case of human operator position control (see Fig. 3 with p-switch connected, and f-switch disconnected), with a few algebraic operations, we obtain

$$\mathbf{Q}_\mathrm{h}(s) = Z_\mathrm{h}(s)(Z_\mathrm{h}(s)+Z_\mathrm{to}(s))^{-1}[X_\mathrm{ref}(s) \quad sZ_\mathrm{to}(s)X_\mathrm{ref}(s)]. \tag{10}$$

Therefore, the conditions for local motor transparency are

$$Z_\mathrm{h}(s) \to \infty \text{ and } Z_\mathrm{to}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s). \tag{11}$$

Similarly, we derived the conditions for remote motor transparency according to $\mathbf{Q_e}(s) = \mathbf{Q_{ref}}(s)$, and for the case of human operator force control (see Fig. 3 with p-switch disconnected and f-switch connected), as summarized in Table I.

B. Transparency Tradeoffs

In this subsection, we show that a linear analysis supports the assertion that it is possible to achieve perceptual and remote transparency without local motor transparency. When subjects probe spring-like force fields, transmission delay causes distortion in their perception of stiffness. We write a linear approximation around a working point for the general effect of teleoperation on the perceived impedance, $\hat{Z}_T(s) = D(s)Z_\mathrm{to}(s)$, where $D(s)$ is the perceptual distortion between the impedance that is presented to the operator, $Z_\mathrm{to}(s)$, and the perceived impedance, $\hat{Z}_T(s)$.

Proposition 1: Let $x_\mathrm{ref}(t)$, $f_\mathrm{ref}(t)$ be a reference trajectory, which is defined to be physically plausible in contact with an environment $Z_\mathrm{e}(s)$, namely:

$$Z_\mathrm{e}(s)sX_\mathrm{ref}(s) = F_\mathrm{ref}(s). \tag{12}$$

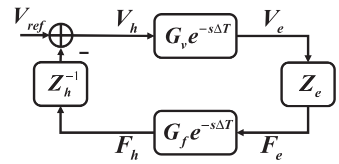

Fig. 4. Block diagram of the simple position–force teleoperation system architecture.

Let $Z_\mathrm{h}(s)$ be linear human operator impedance, and $H(s)$ be the hybrid matrix that represents a linear 1-D dynamics of a general nonideal teleoperation system. In addition, let $\hat{Z}_T(s) = D(s)Z_\mathrm{to}(s)$. Then, it is possible to set the parameters of $H(s)$ such that $\mathrm{MTE}_R = \mathrm{PTE} = 0$, but under these conditions, $\mathrm{MTE}_R \neq 0$.

Proof: Let us examine the case of human operator position control at local side (first row of Table I). We set

$$h_{21}(s)(1 - h_{22}(s)Z_\mathrm{e}(s))^{-1} = 1 \tag{13}$$

the operator increases her impedance such that

$$Z_\mathrm{h}(s) \to \infty \tag{14}$$

and together with (12), we ensure that $\mathbf{Q_e}(s) = \mathbf{Q_{ref}}(s)$. Therefore, according to (5), $\mathrm{MTE}_R = 0$. Next, we select the hybrid matrix parameters such that

$$h_{11}(s) = Z_\mathrm{e}(s)(D(s)^{-1} - h_{12}(s)). \tag{15}$$

Substituting (13) and (15) into (9) yields $Z_\mathrm{to}(s) = h_{11}(s) + h_{12}(s)Z_\mathrm{e} = Z_\mathrm{e}(s)D(s)^{-1}$. In this linear analysis, $\hat{Z}_I(s) = Z_\mathrm{e}(s)$. Therefore, $\hat{Z}_T(s) = \hat{Z}_I(s)$, and substitution to (5) yields $\mathrm{PTE} = 0$. However, now, $Z_\mathrm{to} \neq Z_\mathrm{e}(s)$, and therefore, $Z_\mathrm{to}(s)sX_\mathrm{ref}(s) \neq F_\mathrm{ref}(s)$ and $\mathrm{MTE}_R \neq 0$. □

Proposition 1 demonstrates the essence of our main assertion; however, the derived conditions in this section are not easy to satisfy. Condition (13) cannot be satisfied with a causal system online because of the delay, and requires prediction of future state. Condition (14) is unrealistic: one cannot create infinite impedance using natural human grip. Therefore, in the next section, we will derive realistic conditions for transparency in simplified teleoperation architecture.

V. TRANSPARENCY AND STABILITY IN A SIMPLE TELEOPERATION CHANNEL

In this section, we prove that it is possible to achieve perceptual and remote motor transparency, and maintain stability in a particular, simplified, teleoperation architecture that is depicted in Fig. 4 in a simple task. This system resembles the virtual 1-D teleoperation that we used in our psychophysical studies of perception of delayed stiffness using wrist movements [35], and therefore, we will utilize our experimentally confirmed model, (2).

We model the human operator as a linear time invariant second order mechanical system, i.e.,

$$Z_\mathrm{h}(s) = M_\mathrm{h}s + B_\mathrm{h} + K_\mathrm{h}/s. \tag{16}$$

Such a model for human hand impedance is very common [40], [43], and provides a reasonable approximation for short movements around a working point. We assumed ideal dynamics for the master and slave robots, i.e.,

$$h_{11}(s) = h_{22}(s) = 0 \tag{17}$$

and a nearly ideal transmission line consisting of a scaling and a delay, i.e.,

$$h_{21}(s) = G_{\mathrm{V}} e^{-s\Delta T},\ h_{12}(s) = G_{\mathrm{F}} e^{-s\Delta T},\ \text{and } G_{\mathrm{V}} G_{\mathrm{F}} > 0. \tag{18}$$

Following our psychophysical studies [35], we chose an environment of linear elastic spring:

$$Z_{\mathrm{e}}(s) = K/s. \tag{19}$$

We assume unbiased perception of stiffness in the ideal case, $\hat{K}_I = K$.

We start by assuming that stability is maintained, and deriving the values of force and position gains of the teleoperation channel such that perceptual and motor transparency are satisfied; then, we find the constraints on these values that assure stability. We conclude this section with a numerical example for a stable and transparent system for a particular probing frequency.

A. Perceptual Transparency

For analysis of perceptual transparency, we employ the model (2), to describe an estimation that takes place in the human perceptual system. It is defined for sampled position and force data, and therefore, we assume a specific sampling frequency T_s, and a delay ΔT such that it can be expressed as integer number of samples $n_{\Delta T} = \Delta T / T_s \in \mathbb{Z}^+$. We wish to prove transparency analytically, and therefore, our first step is to derive an analytical, rather than regression based, expression for the perceived stiffness through a channel with gain and delay.

Lemma 1: Consider teleoperation system that satisfies (17)–(19). Then, we can rewrite (2) as

$$\hat{K}_T = K G_{\mathrm{V}} G_{\mathrm{F}} \frac{r_{x_{\mathrm{h}} x_{\mathrm{h}}}(2n_{\Delta T})}{r_{x_{\mathrm{h}} x_{\mathrm{h}}}(0)}. \tag{20}$$

Proof: Rewriting (2) using a notation where $\bullet[i]$ is the ith element in vector $\bullet$, yields $\hat{K}_T = \frac{\sum_{i=1}^{n} f_{\mathrm{h}}[i] x_{\mathrm{h}}[i]}{\sum_{i=1}^{n} (x_{\mathrm{h}}[i])^2} = \frac{r_{f_{\mathrm{h}} x_{\mathrm{h}}}(0)}{r_{x_{\mathrm{h}} x_{\mathrm{h}}}(0)}$, where $r_{xx}(n)$ is the discrete autocorrelation function of the signal $x(t)$ for a lag of n samples, and $r_{xf}(n)$ is the discrete cross-correlation function of the signals $x(t)$ and $f(t)$. Both these functions are calculated from the sampled finite versions of the signals. Following (18), $x_{\mathrm{e}}(t) = G_{\mathrm{V}} x_{\mathrm{h}}(t - \Delta T)$ and $f_{\mathrm{h}}(t) = G_{\mathrm{F}} f_{\mathrm{e}}(t - \Delta T)$. The discrete, sampled, versions of the signals are $x_{\mathrm{e}}[i] = G_{\mathrm{V}} x_{\mathrm{h}}[i - n_{\Delta T}]$ and $f_{\mathrm{h}}[i] = G_{\mathrm{F}} f_{\mathrm{e}}[i - n_{\Delta T}]$. Thus, $\hat{K}_T = \frac{K G_{\mathrm{V}} G_{\mathrm{F}} \sum_{i=1}^{n} x_{\mathrm{h}}[i - 2n_{\Delta T}] x_{\mathrm{h}}[i]}{\sum_{i=1}^{n} (x_{\mathrm{h}}[i])^2} = K G_{\mathrm{V}} G_{\mathrm{F}} \frac{r_{x_{\mathrm{h}} x_{\mathrm{h}}}(2n_{\Delta T})}{r_{x_{\mathrm{h}} x_{\mathrm{h}}}(0)}$. □

Corollary 1: Note that for any signal, $|r_{xx}(n)| < |r_{xx}(0)|$ [41] (the equality holds for periodic signals when n is the period time). Hence, it directly follows that for $G_{\mathrm{V}} = G_{\mathrm{F}} = 1$, stiffness is underestimated (or unbiased for very specific probing frequency and delay), regardless of the nature of probing movements. This is consistent with our experimental results [35], [36]. The unbiased estimation happens for periodic probing with probing frequency such that the probing movement period is identical to the round trip delay, and hence, the operator receives undistorted information.

Lemma 2: Consider a teleoperation system that satisfies (17)–(19). Let $x_{\mathrm{h}}(t) = A_{\mathrm{h}} \sin(\omega t + \phi)$ be a sinusoidal probing movement, and (2) be the perceived stiffness. Then, for every probing frequency such that

$$\omega \Delta T \in [0, 0.25\pi) \cup (\pi(k - 0.25), \pi(k + 0.25))\,;\ k = 1, 2, \ldots \tag{21}$$

$\mathrm{PTE} = 0$ if and only if

$$G_{\mathrm{V}} G_{\mathrm{F}} = 1/\cos(2\omega \Delta T). \tag{22}$$

Proof: The autocorrelation function of $x_{\mathrm{h}}(t) = A_{\mathrm{h}} \sin(\omega t + \phi)$ is $r_{x_{\mathrm{h}} x_{\mathrm{h}}}(\tau) = A_{\mathrm{h}}^2 \cos(\omega \tau)/2$. For $t = nT_s$, we can write a discrete autocorrelation function $r_{x_{\mathrm{h}} x_{\mathrm{h}}}(n) = A_{\mathrm{h}}^2 \cos(\omega T_s n)/2$. We can use (20) to calculate the perceived stiffness (Lemma 1) for any probing frequency $\hat{K}_T = K G_{\mathrm{V}} G_{\mathrm{F}} \cos(2\omega T_s n_{\Delta T}) = K G_{\mathrm{V}} G_{\mathrm{F}} \cos(2\omega \Delta T)$. Thus, $\hat{K}_T = K$ if and only if (22) holds. Substituting $\hat{K}_T = K$ into (7) yields $\mathrm{PTE} = 0$. □

Corollary 2: From an intermediate result in the last proof, it is easy to derive an expression for the perceived stiffness through pure delay (unity gain) channel, $\hat{K}_T = K \cos(2\omega \Delta T)$. The perceptual effect of delay indeed increases with increasing delay and probing frequency, and if the user moves very slowly, the delay will have no effect on perception and action. However, such move and wait strategy is not efficient in many cases for task performance.

We wish to avoid infinite or negative loop gain in our teleoperation system, and therefore, we add (21) as a constraint on probing frequencies that allow perfect perceptual transparency. In practice, perception of mechanical properties of an object is maintained only for small one-way delays of up to 50 ms. These delays are significantly smaller than the typical probing period of about 500 ms or more. Therefore, for practical applications, (21) is not a limiting constraint.

B. Motor Transparency

In our study of the effect of delay on action [24], we asked the subjects to perform an accurate, 1-D, forth and back "slicing" movement with the peak penetration at a predefined target. We use the same task here for the evaluation of motor transparency. We chose this movement because of its simplicity: the performance is evaluated according to the position at a single point in the trajectory—the reversal point. However, it is an important task in various applications of teleoperation; for example, this movement is used in clinical setting for fine needle aspiration of palpable and nonpalpable lesions.

For this simple task, the mixed configuration/force matrix is a single point $\underline{\mathbf{q}} = x_{\mathrm{rev}}$—the position at reversal. This also leads to the simplest weighting matrix $\mathbf{W} = 1$, and a complexity measure $C = 1$. Under these assumptions, (5) is reduced to

$$\mathrm{MTE} = (\max(\underline{\mathbf{x}}) - \max(\underline{\mathbf{x}}_{\mathbf{ref}}))^2. \tag{23}$$

Lemma 3: Consider a stable teleoperation system that satisfies (16)–(19). Let $x_{\mathrm{h}}(t) = A_{\mathrm{h}} \sin(\omega t + \phi)$ and $x_{\mathrm{ref}}(t) = A_{\mathrm{ref}} \sin(\omega t + \phi)$ be sinusoidal actual and reference trajectories. Let (23) be the definition of MTE. Then, $\mathrm{MTE}_R = 0$ if and only if

$$G_V^2 = \frac{(K_\mathrm{h} - M_\mathrm{h}\omega^2 + KG_\mathrm{V}G_\mathrm{F}\cos(2\omega\Delta T))^2}{(B_\mathrm{h}^2\omega^2 + (K_\mathrm{h} - M_\mathrm{h}\omega^2)^2)} + \frac{(B_\mathrm{h}\omega + KG_\mathrm{V}G_\mathrm{F}\sin(2\omega\Delta T))^2}{(B_\mathrm{h}^2\omega^2 + (K_\mathrm{h} - M_\mathrm{h}\omega^2)^2)}. \tag{24}$$

Here, we assumed stability. This assumption can be replaced by the stability conditions from subsection D.

Proof: Under the assumption of pure sinusoidal probing movements, their amplitude determines the maxima of the movements. Hence, for a stable LTI system and probing frequency ω, $\mathrm{MTE} = 0$ if and only if the following condition on the magnitude of the frequency response of the closed-loop transfer function holds

$$|T_\mathrm{cl}(j\omega)|^2 \triangleq |V(j\omega)|^2/|V_\mathrm{ref}(j\omega)|^2 = 1. \tag{25}$$

To describe the remote and local motor transparency, we use Fig. 4, and write the remote and local velocity closed loop transfer functions

$$T_{\mathrm{cl_R}}(s) = \frac{V_\mathrm{e}(s)}{V_\mathrm{ref}(s)} = \frac{(M_\mathrm{h}s^2 + B_\mathrm{h}s + K_\mathrm{h})G_\mathrm{V}e^{-s\Delta T}}{M_\mathrm{h}s^2 + B_\mathrm{h}s + K_\mathrm{h} + G_\mathrm{V}G_\mathrm{F}e^{-s2\Delta T}} \tag{26}$$

$$T_{\mathrm{cl_L}}(s) = \frac{V_\mathrm{h}(s)}{V_\mathrm{ref}(s)} = \frac{(M_\mathrm{h}s^2 + B_\mathrm{h}s + K_\mathrm{h})}{M_\mathrm{h}s^2 + B_\mathrm{h}s + K_\mathrm{h} + G_\mathrm{V}G_\mathrm{F}e^{-s2\Delta T}}. \tag{27}$$

We are interested in remote motor transparency, and hence we demand $|T_{\mathrm{cl_R}}(j\omega)|^2 = 1$, namely

$$\frac{G_\mathrm{V}^2(B_\mathrm{h}^2\omega^2 + (K_\mathrm{h} - M_\mathrm{h}\omega^2)^2)}{(K_\mathrm{h} - M_\mathrm{h}\omega^2 + KG_\mathrm{V}G_\mathrm{F}c(2\omega\Delta T))^2 + (B_\mathrm{h}\omega + KG_\mathrm{V}G_\mathrm{F}s(2\omega\Delta T))^2} = 1$$

where $c(\bullet)$ and $s(\bullet)$ stand for $\cos(\bullet)$ and $\sin(\bullet)$, respectively. Therefore, $\mathrm{MTE}_R = 0$ if and only if (24) satisfied. □

Using (25), it might seem that we adopt the traditional transfer functions analysis. However, the traditional definitions of transparency are written in terms of transfer functions between local and remote sides (positions, forces, or impedances). In contrast, here, we use transfer functions between desired and actual (local or remote) trajectories. A direct result from comparing (26) and (27) is that for any $G_\mathrm{V} \neq 1$, the local motor transparency must be sacrificed for remote motor transparency.

C. Perceptual and Remote Motor Transparency

Proposition 2: Consider a stable teleoperation system that satisfies (16)–(19). Let $x_\mathrm{h}(t) = A_\mathrm{h}\sin(\omega t + \phi)$ and $x_\mathrm{ref}(t) = A_\mathrm{ref}\sin(\omega t + \phi)$ be sinusoidal actual and reference trajectories. Let (23) be the definition of MTE. Then, $\mathrm{MTE}_R = 0$ and $\mathrm{PTE} = 0$ if and only if (22) and

$$G_V^2 = \frac{(K_\mathrm{h} - M_\mathrm{h}\omega^2 + K)^2 + (B_\mathrm{h}\omega + K\tan(2\omega\Delta T))^2}{(B_\mathrm{h}^2\omega^2 + (K_\mathrm{h} - M_\mathrm{h}\omega^2)^2)} \tag{28}$$

are satisfied.

Proof: Follows directly from Lemmas 2 and 3 by substituting (22) into (24).

To conclude, we showed that for the system described in Fig. 4 and a palpation task, under the assumption of stability, for every desired probing frequency of the movements of the human operator that satisfies (21), there exist gains that ensure perceptual and remote motor transparency. These gains can be calculated according to (22) and (28).

D. Stability Analysis

In this subsection, we will derive the conditions for which our assumption of stability holds. We wish to analyze the stability of the closed loop system, with the transfer function (27). We follow [42], and say that the system is stable if the roots of the quasi-polynomial $M_\mathrm{h}s^2 + B_\mathrm{h}s + K_\mathrm{h} + G_\mathrm{V}G_\mathrm{F}e^{-s2\Delta T}$ are in the open left-half plane. For simplification of the analysis, we substitute $\tau = 2\Delta T$, the total loop delay. In [42], the stability of a quasi-polynomial of the form $H_\tau(s) = A(s) + B(s)e^{-s\tau}$, where $\tau > 0$ and $A(S)$ and $B(s)$ are second order real polynomials is analyzed by accounting for $j\omega$-axis crossing of the roots as τ increases. The roots can cross the $j\omega$-axis from left to right (and become unstable) or from right to left (and become stable), and the corresponding frequencies are called switch (ω_σ) and reversal (ω_ρ) frequencies, respectively. Here, we apply their results directly for our simpler quasi-polynomial.

All the constants $M_\mathrm{h}, B_\mathrm{h}, K_\mathrm{h}, G_\mathrm{V}G_\mathrm{F}$ are real and positive, and therefore, the zero delay polynomial has no right-half plane roots. The stability analysis for other delays depends on the existence of switch and reversal crossover frequencies.

Proposition 3: Consider a system with closed loop transfer functions (26) or (27). Then

If

$$\begin{cases} K_\mathrm{h} > KG_\mathrm{V}G_\mathrm{F} \\ \dfrac{K_\mathrm{h}B_\mathrm{h}^2}{M_\mathrm{h}} - \dfrac{B_\mathrm{h}^4}{4M_\mathrm{h}^2} > (KG_\mathrm{V}G_\mathrm{F})^2 \end{cases} \text{ or } \begin{cases} K_\mathrm{h} = KG_\mathrm{V}G_\mathrm{F} \\ \dfrac{K_\mathrm{h}}{M_\mathrm{h}} - \dfrac{B_\mathrm{h}^4}{2M_\mathrm{h}^2} \leq 0 \end{cases} \tag{29}$$

there are no crossover frequencies at all, and the system is delay independent stable (namely, stable for any delay).

If

$$K_\mathrm{h} < KG_\mathrm{V}G_\mathrm{F} \text{ or } \begin{cases} K_\mathrm{h} = KG_\mathrm{V}G_\mathrm{F} \\ \dfrac{K_\mathrm{h}}{M_\mathrm{h}} - \dfrac{B_\mathrm{h}^4}{2M_\mathrm{h}^2} \leq 0 \end{cases} \tag{30}$$

the only crossover frequency is a switch, $\omega_\sigma = \frac{K_\mathrm{h}}{M_\mathrm{h}} - \frac{B_\mathrm{h}^4}{2M_\mathrm{h}^2} + \sqrt{(KG_\mathrm{V}G_\mathrm{F})^2 - \frac{K_\mathrm{h}B_\mathrm{h}^2}{M_\mathrm{h}} + \frac{B_\mathrm{h}^4}{4M_\mathrm{h}^2}}$, and therefore, the system is stable for $\tau < \tau_{\sigma,0}$, $\tau_{\sigma,0} = \frac{1}{\omega_\sigma}\arctan(\frac{\omega_\sigma B_\mathrm{h}}{M_\mathrm{h}\omega_\sigma^2 - K_\mathrm{h}})$.

If

$$\begin{cases} K_\mathrm{h} > KG_\mathrm{V}G_\mathrm{F} \\ \dfrac{K_\mathrm{h}B_\mathrm{h}^2}{M_\mathrm{h}} - \dfrac{B_\mathrm{h}^4}{4M_\mathrm{h}^2} \leq (KG_\mathrm{V}G_\mathrm{F})^2 \end{cases} \tag{31}$$

there are two crossover frequencies, a switch and a reversal, $\omega_{\rho,\sigma} = \frac{K_\mathrm{h}}{M_\mathrm{h}} - \frac{B_\mathrm{h}^4}{2M_\mathrm{h}^2} \mp \sqrt{(KG_\mathrm{V}G_\mathrm{F})^2 - \frac{K_\mathrm{h}B_\mathrm{h}^2}{M_\mathrm{h}} + \frac{B_\mathrm{h}^4}{4M_\mathrm{h}^2}}$, and

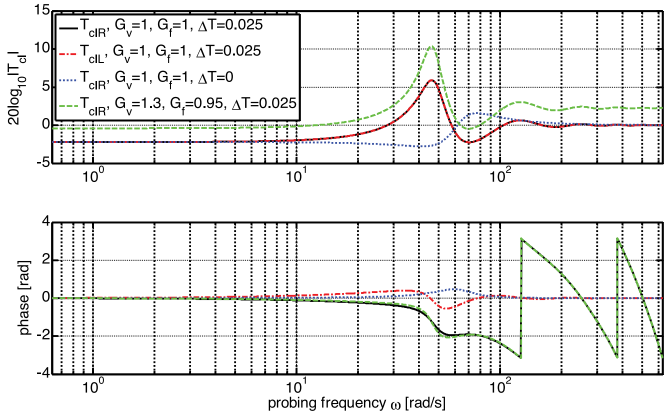

Fig. 5. Frequency responses of the velocity transfer functions for unity and transparency optimized channel gains.

the system is stable for $\tau \in [0, \tau_{\sigma,0}) \cup (\bigcup_{k=1}^{k_0} (\tau_{\rho,k-1}, \tau_{\sigma,k}))$, $\tau_{\bullet,0} = \frac{1}{\omega_\bullet} \arctan(\frac{\omega_\bullet B_{\rm h}}{M_{\rm h}\omega_\bullet^2 - K_{\rm h}})$; $\tau_{\bullet,k} = \tau_{\bullet,0} + \frac{2\pi}{\omega_\bullet}k; k = 0, 1, ...,$ where "$\bullet$" stands for either "σ" or "ρ," $k_0 = \lceil (\frac{1}{\omega_\sigma} - \frac{\tau_{\rho,0} - \tau_{\sigma,0}}{2\pi}) \frac{\omega_\sigma \omega_\rho}{\omega_\sigma - \omega_\rho} \rceil \geq 0$, and $\lceil\ \rceil$ stands for "ceil" (round toward ∞) operation.

Proof: Direct consequence of the analysis in [42], by substituting $A(s) = s^2 + \frac{B_{\rm h}}{M_{\rm h}}s + \frac{K_{\rm h}}{M_{\rm h}}$ and $B(s) = \frac{K G_{\rm V} G_{\rm F}}{M_{\rm h}}$ in (1) in [42].

E. Numerical Example

To illustrate our analytical results, we present a numerical example of a system with parameters that are similar to our psychophysical studies [36]: environment stiffness $K = 145$ N/m and one-way delay of $\Delta T = 25$ ms. The size of the delay was chosen to represent intermediate level of delay which is large enough for inducing significant perceptual and motor effects in typical movement frequencies, but not too large such that the perception of objects (elastic springs) is still maintained. Such a transmission delay is typical of long distance teleoperation on earth (e.g., Operation Linbergh in which surgery was performed via teleoperation between New York and Strasbourg [4]) or to ground-to-earth-orbit teleoperation via radio link [7]. Following [26], [43], we set $M_{\rm h} = 0.15$ kg, $B_{\rm h} = 5$ Ns/m, and $K_{\rm h} = 500$ N/m.

In Fig. 5, the closed loop local and remote motor velocity frequency response are depicted for 0 and 25 ms one-way delay. These are depicted for unity position and force gains, and for $G_{\rm V} = 1.3$, $G_{\rm F} = 0.95$, gains that ensure perceptual and remote motor transparency for probing movement period of 500 ms ($\omega = 4\pi$ rad/s). These frequency responses describe the ratio between actual and desired trajectories, and hence, any deviation from unity gain or zero phase indicates a lack of transparency. The zero delay transfer function is not transparent, but its dependence on frequency is very weak and the phase is close to zero up to 10 Hz, which is much higher than the typical frequencies of human hand movements of up to 3 Hz in various applications [8], [28], [44]. This means that transparency can be achieved by changing the gains of the channel. In the delayed case, the range of weak dependence on frequency is reduced, but the dependence remains moderate in the frequencies range of natural movements. In addition, not surprisingly, the remote transparency suffers from significant lag.

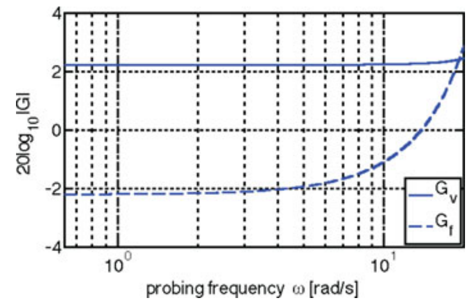

Fig. 6. Optimal teleoperation channel gains for typical frequencies of human hand movement (up to 3 Hz).

In Fig. 6, the optimal gains that ensure perceptual and remote motor transparency are depicted for the typical frequencies of human hand movements. For all the optimal gain values in this range, this system satisfies (29), and hence, stable for any delay. Actually, this is true as long as $G_{\rm V} G_{\rm F} < 1.9$, and the range of possible gains is increased with increasing $K_{\rm h}$, the stiffness of the human operator, relative to K, the stiffness of the environment.

VI. Discussion

We defined a new multidimensional measure for transparency in teleoperation. This measure includes perceptual, local motor, and remote motor transparency components. We propose that perceptual as well as the remote transparency errors should be minimized, by possibly sacrificing the local motor transparency. This is because in many cases of teleoperation, the motor task resides, in the remote environment, and the realistic perception must be rendered in the local environment, where the human operator is located. For any than the ideal channel, for such transparency to be applicable, we rely on the experimental evidence for a gap between human perception and action [22], [23], especially for the case of virtual teleoperation in contact with linear [24] and nonlinear mechanical environments [25]. We proved the feasibility of this process analytically: we derived the ideal requirements to obtain transparency for a general linear two-port channel. For a teleoperation channel with position and force scaling and constant transmission delay, in a palpation and perception of stiffness task, we found analytically gains that assure perfect perceptual and remote motor transparency, and derived the conditions for stability of such system. An interesting observation from this analysis is that stability depends on the operator to maintain sufficient arm impedance relative to environment impedance and delay. There is experimental evidence from previous studies that users indeed adjust their arm impedance to compensate for unstable dynamics of robotic interfaces [45], [46].

A. Applicability and Extensions

We employed a preliminary version of the current framework in an experimental study of teleoperated needle insertion [25].

There, we first identified the effect of delay on the answers of subjects about the perceived stiffness (perceptual transparency) and on their probability of overshooting in the insertion of the needle (motor transparency). Then, we determined the gain necessary for motor transparency based on the experimental evaluation. Because there was no perceptual effect of delay, we kept the total loop gain at unity to maintain perceptual transparency. The environment was nonlinear, and hence the gain that was necessary to achieve transparency was qualitatively different from the gain that was calculated in the current paper. Nevertheless, we did show experimentally the plausibility of our suggested framework: by changing the gain of the teleoperation channel, perceptual and remote motor transparency was achieved.

For motor transparency, we focused on task performance-oriented approach in which local motor transparency is relatively unimportant. This allows the exploitation of the gap between perception and action in the human motor system, and the achievement of perceptual and motor transparency without local motor transparency. We think that this approach is applicable based on previous reports about the differences between cognitive and motor representations [22], [23], and on specific inconsistencies that we found between the effect of delay on declarative and motor-related perception of linear stiffness [24]. A similar gap was central to our design for perceptual and motor transparency in interaction with delayed needle insertion-like force field [25].

In addition, in cases where the baseline gap between perception and action is insufficient for transparency optimization, training of the human operator can be a practical strategy to improve transparency. Such training-induced dissociation between perception and action was reported in many studies of motor adaptation. For example, in adaptation to force fields [47], many of the subjects report that, by the end of training, they no longer feel any external forces, and when the force field is suddenly removed, they report that they felt a force pushing their hand, in the trials where the robot produced no forces.

The perceptual transparency error was defined here only for the local human operator. However, in applications to telerehabilitation [2], or other cases of collaboration via teleoperation [8], [48], [49], in which the remote side is also operated by a human, one should also consider the remote perceptual transparency, namely, the remote operator cannot distinguish between the teleoperation channel and the identity channel, and extend the theory accordingly. In addition, we focused on perception of stiffness. Indeed, it is the dominant mechanical property in natural hand movements [28]. However, addition of inertia and viscosity is a prominent effect of delay [17], [19], [50]. Therefore, in future studies, other mechanical properties should be incorporated into the perceptual error.

B. Limitations and Potential Remedies

The analysis that is presented here is a first attempt to optimize perceptual and motor transparency for a simplified teleoperation channel: a simple environment—pure stiffness, a simple model for the human operator—linear second order system, and a simple motor task—slicing. These simplifying assumptions allowed us to perform a complete analytical analysis of transparency and stability. Further studies are necessary to extend the framework of optimization for perceptual and motor transparency in realistic teleoperation architectures. In the next paragraphs, we discuss how our framework could be modified or extended to address some of the limitations of these assumptions.

We did not take into account the dynamics of the master and slave manipulators and their controllers. Adding linear approximation of their dynamics would not change our results qualitatively, but would complicate some of the expressions. For example, adding a second order model of the master manipulator, that is often approximated as inertia and damping [12], [14], [17], [18], i.e., $Z_{\mathrm{m}}(s) = M_{\mathrm{m}}s^2 + B_{\mathrm{m}}$, would simply increase the inertia and damping parameters of the human side in the denominators of (24) and (26)–(28), and in the analysis of stability in (29)–(31). It would also add nondelayed inertial and viscous components to the perceived impedance of the environment. In many cases, the latter are negligible because often the design requirements for master manipulators are to have small inertia and damping, either by means of mechanical design or control. Adding a similar approximation of the slave manipulator will increase the order of $B(s)$ in the analysis of stability, but this would only complicate the mathematical expressions without changing the qualitative conclusions, e.g., that the user can maintain specific impedance that depends on the parameters of the master and slave devices as well as the environment, and ensure delay independent stability.

As discussed earlier, we did not include local motor transparency in our transparency optimization. However, local motor transparency might become important if a smooth transfer between delayed and nondelayed teleoperation or transfer between different tasks is necessary. In addition, some constraints on local motor performance might result from human factors considerations such as dexterous workspace limitations or fatigue. Our framework can be modified to include optimization for local motor transparency by adding $w_{\mathrm{ML}}\mathrm{MTE}_L$ term to (8). It is important to note that unless the channel is ideal, there is a tradeoff between the local and remote motor transparencies, and their relative importance should be specified in the transparency optimization by using the weights w_{ML} and w_{MR}.

Our result of the optimal velocity and force gains is specific for the task of probing the stiffness of a compliant elastic field with predefined penetration depth. However, most of the practical tasks are more complicated, and therefore, before suggesting a general framework for transparency optimization, the analysis needs to be extended and validated in additional scenarios. Other tasks may include transitions between environments with varying levels of stiffness, including the extreme cases of free space movements ($K = 0$) and rigid contact ($K = \infty$). Because the impedance of the environment is one of the factors that determine the optimal gains for perceptual as well as motor transparencies, to allow for transparent teleoperation, the impedance of the environment should be either known prior to task execution, or estimated online and used to adjust the gains of the teleoperation channel. For the extreme cases, the impedance of the environment also determines the control mode: position control in free space, and force control in rigid contact. The weighting matrix in (5) provides our framework with the necessary flexibility to switch between transparency that is compatible with position control (by setting high weights on the position/orientation components of the configuration vector), force control (by setting high weights on force/torque components of the configuration vector), or combination thereof. In addition, the framework can be extended to allow time varying $\mathbf{W}(t)$ that can be defined prior to the task for different parts of the task, adjusted online by the user, or automatically adjusted online based on estimation of environment properties or user intent. For such complicated scenarios, it is very likely that the optimal gains for transparency could no longer be calculated analytically, and instead, a numerical optimization, or some form of trial-to-trial adaptation of the gains could be utilized.

Tsuji and Tanaka [46], suggested using such adaptive training of the parameters of a controller for an assistive human–robot system, and showed improvement in tracking control performance. Interestingly, an intermediate level of assistance was optimal, because the users responded to assistance by changing their control and impedance. This means that in the design of such adaptive control systems, there is a tradeoff between how much the system parameters should be adapted, and how much of the adaptation is left for the user. There is ample of evidence for adaptation in the human motor system [47], [51], [52], and they should be considered in human-centered system design. Specifically, Krakauer *et al.* showed that users could adapt to a change in the gain of a cursor movement from 1 to 1.5 within less than 10 movements [53], which indicates that adaptive change of controller parameters is applicable. The effect of such changes on the performance of various tasks is yet to be explored, but a recent study of drivers adaptation to a change in steering torques during lane changing maneuvers [54], [55] provided promising results—they showed that the path following accuracy of the drivers was robust to changes in the steering torque feedback, albeit, not to changes in the responsiveness of the car to steering. In addition, in our framework, the effect of such adaptive changes on perception should be addressed.

Similar online adjustments of gains could be useful also to account for the frequency dependence of the optimal gains. For many teleoperation tasks such as explorative palpation to determine the stiffness of remote objects [34]–[36] or remote handshake [8], [9], users tend to perform movements that can be well approximated as sinusoidal inputs with a narrow bandwidth. These are the cases where the current framework is applicable directly by estimating the probing frequency from the initial segment of movement of the user and choosing the appropriate teleoperation gain. For many other tasks, the frequency of movement changes at a slow time scale, and therefore, the frequency can be estimated online and used to adaptively change the teleoperation gains. The movements of human operators in many applications are limited to a narrow range of frequencies between 1–3 Hz [8], [28], [44]. In our numerical example, this is a region where the optimal force gain changes rapidly, which may limit the success of such adaptation if the frequency of movement changes too fast.

For the rare case of higher frequencies, our analysis of motor transparency and stability holds regardless to value of the delay, but the perceptual transparency holds only as long as (21) is satisfied. This means that for one-way delay of 25 ms, our perceptual transparency optimization holds for movement frequencies up to 5 Hz. Such high frequencies result either from user tremor or hard environment contact transients. The first case could be easily treated by low-pass filtering of the movement of the user before transmission to remote side. The contact-related high frequencies could have interesting implications [56], but their treatment would require nonlinear system description, and therefore, is left outside of the scope of the current paper.

C. Human Operator Model

In our study, we addressed a simple second order linear model for the impedance of the human operator. In practice, it is known that the human operator impedance is not linear, and that it changes with posture [57], [58], task [59], [60], environment dynamics [45], [46], and more, by means of cocontraction patterns between different muscles of the arm, and adjustment of reflex gains. In our framework, the optimal parameters of the teleoperation channel as well as the overall system stability depend on the impedance of the operator. Therefore, the techniques for estimating the impedance of the operator during posture maintenance [57], [61] and movement [62], [63] can be used for the adjustment of channel parameters. The recent attempts to incorporate the impedance of the user in teleoperation control showed promising results. For example, to allow the user to adjust the impedance of the slave robot by changing the grip force on the master stylus was shown to be beneficial over any fixed impedance of the slave [32]. In a different study, the impedance of the slave robot was adjusted based on the measurement of muscle activation using electromyography [64]. In addition, in cases where it is impossible to find a gain that will optimize transparency and maintain stable system, the users can be trained to change their impedance such that the overall system transparency and stability will be improved.

Future studies could extend the simplified human operator model in Fig. 3 and our linear second order approximation to more realistic models. For example, we could include separate contribution of intrinsic mechanical properties of muscles and reflex pathways [60], [61], [65], internal inverse and forward models [47], [55], [66], delayed feedback [67], or optimal feedback control [68], [69]. Nonlinear models, e.g., Hill-type model, or one-fifth power damping [70], could be considered to describe the muscles. In addition, we assumed a reference trajectory that optimizes task performance. Indeed, many theories in human motor control employ optimality principles [69]. However, which cost does the motor system optimize in motor planning [71], and whether trajectories are computed prior to movement in open loop, or are optimized online in closed loop depending on sensory feedback [69], are still open questions. Importantly, the most realistic and accurate model of the human operator is not necessary the best model to use in our framework, because it might be computationally too complicated and will not allow analytic or fast enough numeric optimization of transparency. Exploring the benefits, limitations, and tradeoffs of using these different levels of user approximations are left to future studies.

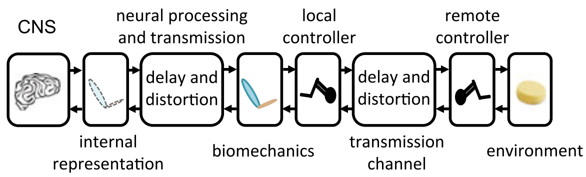

Fig. 7. Schematic representation of the extended teleoperation framework. The "human operator" block from Fig. 1 was replaced with additional teleoperation channel connecting the CNS of the user with his hand.

Finally, regardless to which implementation of human operator model is chosen, it can be incorporated into the framework as another two-port teleoperation channel that connects the central nervous system of the users with their limbs; namely, the schematic view in Fig. 1 can be extended into the schematic view that is presented in Fig. 7. Such conceptual view of the system was suggested before [72], and moreover, in [73], [74], a specific architecture of "wave variables" teleoperation and its physiological meaning was suggested as a model of the human motor system.

VII. Conclusion

We suggest a new multidimensional measure for transparency in teleoperation that focuses on optimizing the performance of the coupled human operator teleoperation channel system, and includes perceptual, local motor, and remote motor transparencies. We derived the ideal transparency conditions for the general linear case, and found the control parameters that assure perfect perceptual and remote motor transparency in the case of a teleoperation channel with position and force scaling and constant transmission delay, in a palpation and perception of stiffness task. We found that in this case, the stability depends on the operator maintaining sufficient arm impedance relative to environment impedance and delay. We discussed the possible extensions of this framework such that it can be implemented in a wider range of realistic teleoperation tasks.

Achieving transparency of a teleoperation system is a daunting challenge that is yet to be solved. We strongly believe that understanding the human motor control is essential in order to develop a useful system, and hope that the definitions and tools provided in this study would be useful in future development of teleoperation systems.

Acknowledgment

The authors thank Prof. A. Okamura for valuable comments on this paper.

References

[1] M. D. Duong, K. Terashima, T. Miyoshi, and T. Okada, "Rehabilitation system using teleoperation with force-feedback-based impedance adjustment and emg-moment model for arm muscle strength assessment," *J. Robot. Mechatron.*, vol. 22, no. 1, pp. 10–20, 2010.

[2] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 2, pp. 102–108, Jun. 2002.

[3] M. C. Cavusoglu, F. Tendick, M. Cohn, and S. S. Sastry, "A laparoscopic telesurgical workstation," *IEEE Trans. Robot. Autom.*, vol. 15, no. 4, pp. 728–739, Aug. 1999.

[4] J. Marescaux, J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S. E. Butner, and M. K. Smith, "Transatlantic robot-assisted telesurgery," *Nature*, vol. 413, no. 6854, pp. 379–380, 2001.

[5] G. Hirzinger, B. Brunner, J. Dietrich, and J. Heindl, "Sensor-based space robotics-rotex and its telerobotic features," *IEEE Trans. Robot. Autom.*, vol. 9, no. 5, pp. 649–663, Oct. 1993.

[6] T. Imaida, Y. Yokokohji, T. Doi, M. Oda, and T. Yoshikawa, "Ground-space bilateral teleoperation of ets-vii robot arm by direct bilateral coupling under 7-s time delay condition," *IEEE Trans. Robot. Autom.*, vol. 20, no. 3, pp. 499–511, Jun. 2004.

[7] D. Reintsema, K. Landzettel, and G. Hirzinger, "DLR's advanced telerobotic concepts and experiments for on-orbit servicing," in *Advances in Telerobotics*, M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, Eds. Heidelberg, Germany: Springer Tract in Advanced Robotics, 2007, vol. 31, pp. 323–345.

[8] A. Karniel, I. Nisky, G. Avraham, B.-C. Peles, and S. Levy-Tzedek, *A Turing-Like Handshake Test for Motor Intelligence* (Series Lecture Notes in Computer Science 6191). Heidelberg, Germany: Springer-Verlag, 2010, pp. 197–204.

[9] G. Avraham, I. Nisky, H. Fernandes, D. Acuna, K. Kording, G. Loeb, and A. Karniel, "Towards perceiving robots as humans—Three handshake models face the turing-like handshake test," *IEEE Trans. Hapt.*, vol. 5, no. 3, pp. 196–207, Jul.–Sep. 2012.

[10] B. Hannaford, "Stability and performance tradeoffs in bi-lateral telemanipulation," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1989, pp. 1764–1767.

[11] S. Sirouspour and A. Shahdi, "Model predictive control for transparent teleoperation under communication time delay," *IEEE Trans. Robot.*, vol. 22, no. 6, pp. 1131–1145, Dec. 2006.

[12] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May 1989.

[13] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robot. Autom.*, vol. 9, no. 5, pp. 624–627, Oct. 1993.

[14] Y. Yokokohji and T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment," *IEEE Trans. Robot. Autom.*, vol. 10, no. 5, pp. 605–620, Oct. 1994.

[15] H.-K. Lee and M. J. Chung, "Adaptive controller of a master-slave system for transparent teleoperation," *J. Robot. Syst.*, vol. 15, no. 8, pp. 465–475, 1998.

[16] S. E. Salcudean, M. Zhu, W.-H. Zhu, and K. Hashtrudi-Zaad, "Transparent bilateral teleoperation under position and rate control," *Int. J. Robot. Res.*, vol. 19, no. 12, pp. 1185–1202, 2000.

[17] G. Niemeyer and J.-J. E. Slotine, "Telemanipulation with time delays," *Int. J. Robot. Res.*, vol. 23, no. 9, pp. 873–890, 2004.

[18] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, 2006.

[19] J. Park and O. Khatib, "A haptic teleoperation approach based on contact force control," *Int. J. Robot. Res.*, vol. 25, nos. 5–6, pp. 575–591, 2006.

[20] S. Sirouspour and A. Shahdi, "Discrete-time linear quadratic gaussian control for teleoperation under communication time delay," *Int. J. Robot. Res.*, vol. 25, no. 2, pp. 187–202, 2006.

[21] P. G. Griffiths and R. B. Gillespie, "Characterizing teleoperator behavior for feedback design and performance analysis," in *Proc. Symp. Hapt. Interf. Virt. Environ., Teleoperat. Syst.*, 2008, pp. 273–280.

[22] M. A. Goodale and A. D. Milner, "Seperate visoual pathways for perception and action," *Trends Neurosci.*, vol. 15, no. 1, pp. 20–25, 1992.

[23] D. P. Carey, "Do action systems resist visual illusions?" *Trends Cognit. Sci.*, vol. 5, no. 3, pp. 109–113, 2001.

[24] A. Pressman, I. Nisky, A. Karniel, and F. A. Mussa-Ivaldi, "Probing virtual boundaries and the perception of delayed stiffness," *Adv. Robot.*, vol. 22, no. 1, pp. 119–140, 2008.

[25] I. Nisky, A. Pressman, C. M. Pugh, F. A. Mussa-Ivaldi, and A. Karniel, "Perception and action in teleoperated needle insertion," *IEEE Trans. Hapt.*, vol. 4, no. 3, pp. 155–166, May/Jun. 2011.

[26] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "Perceptuo-motor transparency in bilateral teleoperation," in *Proc. ASME Conf. Eng. Syst. Design Anal.*, 2008, vol. 2, pp. 449–456.

[27] S. Hirche and M. Buss, "Human perceived transparency with time delay," *Advances in Telerobotics,* M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, Eds. Heidelberg, Germany: Springer Tract in Advanced Robotics, 2007, vol. 31, pp. 191–209.

[28] G. De Gersem, H. Van Brussel, and F. Tendick, "Reliable and enhanced stiffness perception in soft-tissue telemanipulation," *Int. J. Robot. Res.*, vol. 24, no. 10, pp. 805–822, 2005.

[29] M. C. Cavusoglu, A. Sherman, and F. Tendick, "Design of bilateral teleoperation controllers for haptic exploration and telemanipulation of soft

environments," *IEEE Trans. Robot. Autom.*, vol. 18, no. 4, pp. 641–647, Aug. 2002.

[30] D. Botturi, M. Vicentini, M. Righele, and C. Secchi, "Perception-centric force scaling in bilateral teleoperation," *Mechatronics*, vol. 20, no. 7, pp. 802–811, 2010.

[31] H. I. Son, T. Bhattacharjee, and H. Hashimoto, "Enhancement in operator's perception of soft tissues and its experimental validation for scaled teleoperation systems," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 99, pp. 1–14, Dec. 2010.

[32] D. S. Walker, J. K. Salisbury, and G. Niemeyer, "Demonstrating the benefits of variable impedance to telerobotic task execution," in *Proc. Int. Conf. Robot. Autom.*, 2011, pp. 1348–1353.

[33] M. C. Yip, M. Tavakoli, and R. D. Howe, "Performance analysis of a haptic telemanipulation task under time delay," *Adv. Robot.*, vol. 25, pp. 651–673, 2011.

[34] A. Pressman, L. Welty, A. Karniel, and F. A. Mussa-Ivaldi, "Perception of delayed stiffness," *Int. J. Robot. Res.*, vol. 26, pp. 1191–1203, 2007.

[35] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "A regression and boundary-crossing-based model for the perception of delayed stiffness," *IEEE Trans. Hapt.*, vol. 1, no. 2, pp. 73–82, Jul.–Dec. 2008.

[36] I. Nisky, P. Baraduc, and A. Karniel, "Proximodistal gradient in the perception of delayed stiffness," *J. Neurophysiol.*, vol. 103, no. 6, pp. 3017–3026, 2010.

[37] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *Int. J. Robot. Res.*, vol. 20, no. 6, pp. 419–445, 2001.

[38] K. Hashtrudi-Zaad and S. E. Salcudean, "Transparency in time-delayed systems and the effect of local force feedback for transparent teleoperation," *IEEE Trans. Robot. Autom.*, vol. 18, no. 1, pp. 108–114, Feb. 2002.

[39] L. A. Jones and I. W. Hunter, "A perceptual analysis of stiffness," *Exp. Brain Res.*, vol. 79, no. 1, pp. 150–6, 1990.

[40] J. J. Abbott and A. M. Okamura, "Stable forbidden-region virtual fixtures for bilateral telemanipulation," *J. Dyn. Syst., Meas., Control*, vol. 128, no. 1, pp. 53–64, 2006.

[41] J. G. Proakis and D. G. Manolakis, *Introduction to Digital Signal Processing*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1988.

[42] E. Malakhovski and L. Mirkin, "On stability of second-order quasi-polynomials with a single delay," *Automatica*, vol. 42, no. 6, pp. 1041–1047, 2006.

[43] K. J. Kuchenbecker, J. G. Park, and G. Niemeyer, "Characterizing the human wrist for improved haptic interaction," in *Proc. Int. Mech. Eng. Congr. Expo.*, vol. 2, no. 42017, pp. 1–8, 2003.

[44] J. Brown, J. Rosen, L. Chang, M. Sinanan, and B. Hannaford, "Quantifying surgeon grasping mechanics in laparoscopy using the blue dragon system," *Studies Health Technol. Inf.*, vol. 98, pp. 34–36, 2004.

[45] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature*, vol. 414, no. 6862, pp. 446–449, 2001.

[46] T. Tsuji and Y. Tanaka, "Tracking control properties of human-robotic systems based on impedance control," *IEEE Trans. Syst., Man Cybern. A, Syst., Humans*, vol. 35, no. 4, pp. 523–535, Jul. 2005.

[47] R. Shadmehr and F. A. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *J. Neurosci.*, vol. 14, no. 5, pp. 3208–3224, 1994.

[48] J. Kim, H. Kim, B. K. Tay, M. Muniyandi, M. A. Srinivasan, J. Jordan, J. Mortensen, M. Oliveira, and M. Slater, "Transatlantic touch: A study of haptic collaboration over long distance," *Presence: Teleoperator Virtual Environ.*, vol. 13, no. 3, pp. 328–337, 2004.

[49] R. Groten, D. Feth, A. Peer, and M. Buss, "Shared decision making in a collaborative task with reciprocal haptic feedback—An efficiency-analysis," in *Proc. Int. Conf. Robot. Autom.*, 2010, pp. 1834–1839.

[50] M. Rank, Z. Shi, and S. Hirche, "Perception of delay in haptic telepresence systems," *Presence: Teleoperator Virtual Environ.*, vol. 19, no. 5, pp. 389–399, 2010.

[51] J. W. Krakauer and P. Mazzoni, "Human sensorimotor learning: Adaptation, skill, and beyond," *Curr. Opin. Neurobiol.*, vol. 21, no. 4, pp. 636–644, 2011.

[52] R. Shadmehr and S. Mussa-Ivaldi, *Biological Learning and Control: How the Brain Builds Representations, Predicts Events, and Makes Decisions*. Cambridge, MA, USA: MIT Press, 2012.

[53] J. W. Krakauer, Z. M. Pine, M.-F. Ghilardi, and C. Ghez, "Learning of visuomotor transformations for vectorial planning of reaching trajectories," *J. Neurosci.*, vol. 20, no. 23, pp. 8916–8924, 2000.

[54] A. J. Pick and D. J. Cole, "Driver steering and muscle activity during a lane-change manoeuvre," *Veh. Syst. Dyn.*, vol. 45, no. 9, pp. 781–805, 2007.

[55] A. J. Pick and D. J. Cole, "A mathematical model of driver steering control including neuromuscular dynamics," *J. Dyn. Syst., Meas., Contr.*, vol. 130, no. 3, pp. 031004–031004, 2008.

[56] K. J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving contact realism through event-based haptic feedback," *IEEE Trans. Vis. Comput. Graph.*, vol. 12, no. 2, pp. 219–230, Mar./Apr. 2006.

[57] F. Mussa-Ivaldi, N. Hogan, and E. Bizzi, "Neural, mechanical, and geometric factors subserving arm posture in humans," *J. Neurosci.*, vol. 5, no. 10, pp. 2732–2743, 1985.

[58] T. Tsuji, P. Morasso, K. Goto, and K. Ito, "Human hand impedance characteristics during maintained posture," *Biolog. Cybern.*, vol. 72, no. 6, pp. 475–485, 1995.

[59] H. Gomi and R. Osu, "Task-dependent viscoelasticity of human multijoint arm and its spatial characteristics for interaction with environments," *J. Neurosci.*, vol. 18, no. 21, pp. 8965–8978, 1998.

[60] W. Mugge, D. Abbink, A. Schouten, J. A. Dewald, and F. T. Helm, "A rigorous model of reflex function indicates that position and force feedback are flexibly tuned to position and force tasks," *Exp. Brain Res.*, vol. 200, nos. 3–4, pp. 325–340, 2010.

[61] E. de Vlugt, A. C. Schouten, and F. C. T. van der Helm, "Quantification of intrinsic and reflexive properties during multijoint arm posture," *J. Neurosci. Methods*, vol. 155, no. 2, pp. 328–349, 2006.

[62] E. Burdet, R. Osu, D. W. Franklin, T. Yoshioka, T. E. Milner, and M. Kawato, "A method for measuring endpoint stiffness during multi-joint arm movements," *J. Biomech.*, vol. 33, no. 12, pp. 1705–1709, 2000.

[63] D. Piovesan, A. Pierobon, P. DiZio, and J. R. Lackner, "Measuring multi-joint stiffness during single movements: Numerical validation of a novel time-frequency approach," *PLoS ONE*, vol. 7, no. 3, p. e33086, 2012.

[64] A. Ajoudani, N. Tsagarakis, and A. Bicchi, "Tele-impedance: Teleoperation with impedance regulation using a body–machine interface," *Int. J. Robot. Res.*, vol. 31, no. 13, pp. 1642–1656, 2012.

[65] A. C. Schouten, W. Mugge, and F. C. T. van der Helm, "Nmclab, a model to assess the contributions of muscle visco-elasticity and afferent feedback to joint dynamics," *J. Biomech.*, vol. 41, no. 8, pp. 1659–1667, 2008.

[66] M. Kawato, "Internal models for motor control and trajectory planning," *Curr. Opin. Neurobiol.*, vol. 9, pp. 718–727, 1999.

[67] L. Botzer and A. Karniel, "Feedback and feedforward adaptation to visuomotor delay during reaching and slicing movements," *Eur. J. Neurosci.*, vol. 38, no. 1, pp. 2108–2123, 2013.

[68] R. Shadmehr and J. Krakauer, "A computational neuroanatomy for motor control," *Exp. Brain Res.*, vol. 185, no. 3, pp. 359–381, 2008.

[69] E. Todorov, "Optimality principles in sensorimotor control," *Nat. Neurosci.*, vol. 7, no. 9, pp. 907–915, 2004.

[70] A. G. Barto, A. H. Fagg, N. Sitkoff, and J. C. Houk, "A cerebellar model of timing and prediction in the control of reaching," *Neural Comput.*, vol. 11, no. 3, pp. 565–94, 1999.

[71] T. Flash and T. J. Sejnowski, "Computational approaches to motor control," *Curr. Opin. Neurobiol.*, vol. 11, no. 6, pp. 655–662, 2001.

[72] R. B. Gillespie and S. O'Modhrain, "Embodied cognition as a motivating perspective for haptic interaction design: A position paper," in *Proc. World Hapt. Conf.*, 2011, pp. 481–486.

[73] J. McIntyre and J.-J. E. Slotine, "Does the brain make waves to improve stability?" *Brain Res. Bull.*, vol. 75, no. 6, pp. 717–722, 2008.

[74] S. G. Massaquoi and J.-J. E. Slotine, "The intermediate cerebellum may function as a wave-variable processor," *Neurosci. Lett.*, vol. 215, no. 1, pp. 60–64, 1996.

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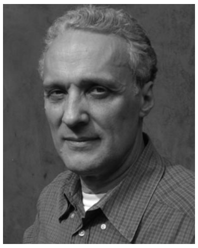

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