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PERCEPTUO-MOTOR TRANSPARENCY IN BILATERAL TELEOPERATION

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ABSTRACT
In bilateral teleoperation, the operator holds a local robot which determines the motion of a remote robot and continuously receives delayed force feedback. Transparency is a measure of teleoperation system fidelity. The ideal teleoperator system is the identity channel, in which there is neither delay nor distortion. During the last decades transparency was widely analyzed using two-port hybrid representation of the system in Laplace domain. Such representations define hybrid matrix that maps between the transmission channel inputs and outputs. However, in measuring transparency one should consider also the human operator, and therefore we propose a multidimensional measure of transparency which takes into account: i) Perceptual transparency: The human operator cannot distinguish when the teleoperation channel is being replaced by an identity channel. ii) Local Motor transparency: The movement of the operator does not change when the teleoperation channel is replaced by an identity channel. iii) Remote transparency: The movement of the remote robot does not change when the teleoperation channel is replaced by an identity channel. We hypothesize that by selecting filters and training protocol it is possible to obtain perceptually transparent teleoperation (i) and remote motor transparency (iii) without local motor transparency (ii), namely, to *transparentize* the system. We formally define the transparency error, analyze this process in the linear case, and simulate simplified teleoperation system according to typical experimental results in our previous studies about perception of delayed stiffness. We believe that these tools are essential in developing functional teleoperation systems.

1. INTRODUCTION
Bilateral (force reflecting) teleoperation allows human operators to determine the motion of a remote slave robot by moving a local master robot and feeling the forces reflected from the slave to the master. Obviously, the properties of the channel transmitting the information from the local to the remote side and back may influence system quality. But, while channel properties have been analyzed, the influence of the human operators and their perceptual and motor capabilities has been largely overlooked. We aim to utilize the adaptive responses of the human operator to generate perceptually transparent and functional teleoperation systems. In such systems operator intentions will be accurately executed in the remote environment, and the remote environment will be accurately perceived by the operator. Telemedicine, such as remote rehabilitation and telesurgery, are probably the primary applications, but a broader range of users will eventually enjoy the enhancements in telerobotics and telepresence technologies of the future, e.g., by handling hazardous materials from safe distance, and the addition of a personal touch to standard telecommunications.

Teleoperation systems are typically described as two-port networks, usually represented by a hybrid parameters model [1-

5]. Transparency is a measure of teleoperation system fidelity, and various definitions and conditions for transparency have been presented. Some authors define ideal transparency according to network functions, such as impedance or admittance [3, 4, 6]. Others define transparency by correspondence of position and force signals [7]. In the linear case, the channel is described as follows:

$$\begin{pmatrix} F_h(s) \\ V_e(s) \end{pmatrix} = \begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix} \cdot \begin{pmatrix} V_h(s) \\ F_e(s) \end{pmatrix} \quad (1)$$

where F_h, F_e are the forces and V_h, V_e are the velocities for the local and remote sides respectively, and *s* is the Laplace domain complex frequency. An ideal channel (i.e. completely transparent), or identity channel, is defined by the requirements of equal force and equal velocity of the two sides. The hybrid matrix for the identity channel and a channel with delay are:

$$H_{ideal}(s) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \; H_{delayed}(s) = \begin{pmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{pmatrix} \quad (2)$$

Generally, ideal transparency conditions are unattainable [8], particularly in the presence of transmission delays [9]. Moreover, the design goals of stability and transparency are in mutual conflict, and as such, there is a stability/transparency, or stability/performance tradeoff [3, 8, 10]. In the presence of delay achieving transparency essentially requires prediction, which is not practical [4].

In some studies a human operator was included by considering force perception thresholds [10]. These studies used a just noticeable difference (JND) for mechanical properties and time delay [5, 8], or frequency dependent weighted relative change in environment impedance [5, 11]. Other approaches consider the human operator by various coordinates transformations between the human hand and the remote robot, e.g. the hidden robot concept [12]. More abstract transformations involving gesture recognition were recently proposed[13]. However, these do not address force feedback.

We have recently addressed the influence of delay on the perception of mechanical stiffness [14-18]. In a forced choice paradigm subjects were presented with two spring-like force fields and were asked to identify the stiffer one. For one field the force was proportional to the penetration into the field, but in the second the force was proportional to a penetration a few tens of milliseconds earlier. We found that subjects tend to overestimate delayed stiffness [16]. Additionally, we found that shifting the boundary also modified stiffness perception [17]. More recently we found that when subjects did not cross a boundary – i.e. when their hand remained inside an elastic field all the time – they tend to underestimate delayed stiffness [18]. Therefore, the outcome of the estimation depends on the boundary crossing. To account for these results we proposed a unifying computational model of stiffness perception that describes haptic perception as an active process that combines the operation of a force and of a position control system operating concurrently [15, 18]. When moving without crossing the boundary, our best model was the slope of force over position regression. Probing inside the boundary as well as occasionally crossing the boundary resulted in a weighted sum of the regression slopes of force over position (FP) and the inverse of position over force (PF), which yield underestimation and overestimation respectively [15, 18]. According to this model the perceived stiffness is:

$$\hat{K} = \alpha \hat{K}_{PF} + (1-\alpha)\hat{K}_{FP} \quad (3)$$

where α is the boundary crossing ratio, namely $\alpha = 0$ when moving only inside the field, and $\alpha = 1$ when each and every movement crossed the boundary inside and out. We also found inconsistency between declarative and motor-related perception of stiffness [17]. Such inconsistency was recently reported in other tasks [19, 20].

Based on these findings, we suggest that a multidimensional measure of transparency is necessary. Such a measure should account for aspects of perception as well as action. We consider the following three aspects of transparency:

(i) *Perceptual transparency:* The human operator cannot distinguish between the channel and an identity channel.

(ii) *Local motor transparency:* The movement of the operator is equal to his/her movements with an identity channel.

(iii) *Remote motor transparency:* The movement of the remote robot is equal to the resultant movement with the identity channel.

Based on our results concerning the difference between perception and action [17], we hypothesize that for a wide family of teleoperation channels it is possible to obtain perceptually transparent teleoperation (i) and remote motor transparency (iii) without local motor transparency (ii). In practice, such a goal is attainable by changing either the local or remote controllers, or the human operator by means of training. We call the process of selecting optimal controllers and training protocols *transparentizing*. In this paper we formally describe this transparentizing process and provide a first analysis and simulation to demonstrate its potential benefit.

The rest of the paper is organized as follows: in the next section we describe our proposed multidimensional transparency measure mathematically. Then we define the interconnections between the classical two-port representation parameters and our transparency measure. This section is followed by a theoretical example of teleoperation system transparentization, and simulations of transparentizing more realistic system. Finally, a brief discussion concludes the paper.

2. MULTI-DIMENSIONAL TRANSPARENCY MEASURE

Consider a remote surgical procedure that requires cutting some soft connective tissue while avoiding stiffer vessels and muscle tissue. In this scenario there are two actions (probing and cutting) and two perceptions (soft or stiff tissue). The surgeon acts in a local virtual environment but the actual procedure is done on a remote patient via a telemanipulation system. Three potential problems can arise due to an imperfect channel. (i) The surgeon can *misperceive* soft connective tissue as stiff muscle/vessel tissue or vice versa. (ii) The surgeon can *perform* a virtual cut *locally* when she wishes to probe the tissue. (iii) The surgeon can actually *cut* the real *remote* tissue when she intends to probe it or vice versa. These three problems correspond to the three aspects of transparency.

2.1 Motor Transparency Error

The following definitions refer to both local and remote transparencies. Consider the general state vector *q(t)* which consists of the position force and angular torque:

$$q(t) = \begin{pmatrix} x & y & z & f_x & f_y & f_z & \tau_x & \tau_y & \tau_z \end{pmatrix}(t) \quad (4)$$

For a specific temporal window and sampling rate we observe the following state matrix:

$$\underline{q} = \begin{pmatrix} q(t_1)^T & q(t_2)^T & \cdots & q(t_N)^T \end{pmatrix}^T \quad (5)$$

and define the motor transparency error based on the distance between the target reference trajectory $\underline{q}_{ref}$ and the actual (local or remote) trajectories using the teleoperation channel $\underline{q}_T$. Since noise always exists we compare the actual trajectory to the trajectory through the ideal channel, $\underline{q}_I$ and propose the following measure for the Motor Transparency Error:

$$MTE = \frac{\left\| \underline{q}_T - \underline{q}_{ref} \right\|_* - \left\| \underline{q}_I - \underline{q}_{ref} \right\|_*}{C} \quad (6)$$

where $\| \|_*$ is a norm, such as the Mahalanobis distance, and C is a complexity measure of the task, such as the length or duration of the movement.

2.2 Perceptual Transparency Error

We concentrate on the perception of stiffness, since in telesurgery and telemedicine accurately perceiving the stiffness of tissues is critical for diagnosis and safety of operation; moreover, in natural movements' frequencies stiffness is the dominant mechanical property [5].

Since human perception of stiffness follows Webber's law [5, 21, 22], we use a relative measure for perceptual transparency, and define the Perceptual Transparency Error:

$$PTE = \left| \frac{\hat{K}_T - \hat{K}_I}{\hat{K}_I} \right| \quad (7)$$

where $\hat{K}_I$ and $\hat{K}_T$ are the estimation of the perceived stiffness through the identity and the transmission channels respectively. We assume estimation of stiffness according to Eq. (3), namely, for movement in a single dimension:

$$\hat{K} = \alpha \left((\underline{f}_{ref}{}^T \underline{f}_{ref})^{-1} \underline{f}_{ref}{}^T \underline{x}_h \right)^{-1} + (1-\alpha)(\underline{x}_{ref}{}^T \underline{x}_{ref})^{-1} \underline{x}_{ref}{}^T \underline{f}_h \quad (8)$$

Note that we defined the perceptual stiffness only for the local human operator (the subscript *h* indicates the subjects hand).

3. THEORETICAL TRANSPARENTIZING

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

$$H = \underset{\substack{h_{ij} \\ i=1,2 \\ j=1,2}}{\arg\min} \left\{ w_P PTE + w_{MR} MTE_R \right\} \quad (9)$$

$$\text{s.t. } MTE_L \text{ meets human factor constraints}$$

where the *R* and *L* subscripts refer to remote and local respectively, and where w_P and w_{MR} are the weights for perceptual and motor remote transparency respectively. In this section we demonstrate the interconnections between our suggested transparency measures in the linear case.

3.1 Two-port representation

Teleoperation systems are typically described as two-port networks (see Fig. 1 and Eq. (1)). Using a few algebraic

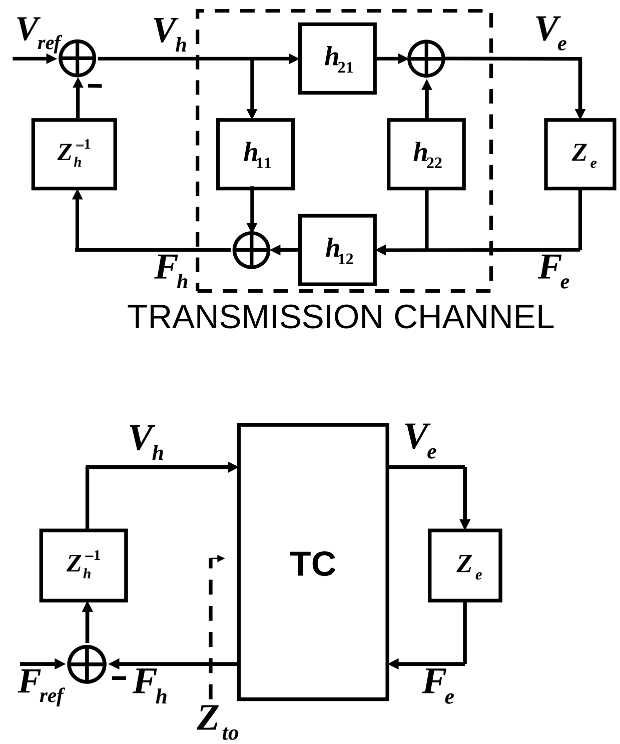

Figure 1: Two port representation of teleoperation system under position (A) and force (B) control. Z_h and Z_e are human and environment impedances respectively. Encapsulated into the dashed frame in A is a detailed block representation of the hybrid (H) matrix components. Z_{to} in B is the impedance presented to the operator. In ideal teleoperation system Z_{to}=Z_e

Table 1: Ideal conditions for motor transparency

Control method	*Local motor transparency*	*Remote transparency*
Position control	$Z_h(s)\to\infty$ $Z_{to}(s)sX_{ref}(s)=F_{ref}(s)$	$\frac{h_{21}(s)}{1-h_{22}(s)Z_e(s)}\cdot\frac{Z_h(s)}{Z_h(s)+Z_{to}(s)}=1$ $Z_e(s)sX_{ref}(s)=F_{ref}(s)$
Force control	$Z_h(s)\to 0$ $Z_{to}(s)sX_{ref}(s)=F_{ref}(s)$	$\frac{h_{21}(s)}{1-h_{22}(s)Z_e(s)}\cdot\frac{Z_e(s)}{Z_{to}(s)+Z_h(s)}=1$ $Z_e(s)sX_{ref}(s)=F_{ref}(s)$

manipulations on Eq. (1) we can write the impedance observed by the human operator as:

$$Z_{to}(s)=h_{11}(s)+\frac{h_{12}(s)h_{21}(s)}{1-Z_e(s)h_{22}(s)}Z_e(s) \tag{10}$$

We next derive ideal conditions for motor transparency. For simplicity in the following analysis we will consider one dimensional movement and forces (i.e., no torques), such that $q(t)=\begin{pmatrix}x(t) & f(t)\end{pmatrix}$ and its Laplace domain is $Q(s)=\begin{pmatrix}X(s) & F(s)\end{pmatrix}$.

Figure 1 illustrates two possible control strategies which we consider when deriving the conditions for motor transparency. The condition for perfect local motor transparency is $q_h(t)=q_{ref}(t)$ or $Q_h(s)=Q_{ref}(s)$. From Fig. 1A, and a few algebraic operations we obtain

$$\begin{aligned}Q_h(s)&=X_h(s)\begin{bmatrix}1 & sZ_{to}(s)\end{bmatrix}=\\&X_{ref}(s)\begin{bmatrix}1 & sZ_{to}(s)\end{bmatrix}-Z_h^{-1}(s)Z_{to}(s)Q_h(s)\end{aligned} \tag{11}$$

$$Q_h(s)=\left[Z_h(s)\,\|\,Z_{to}(s)\right]\begin{bmatrix}\frac{X_{ref}(s)}{Z_{to}(s)} & sX_{ref}(s)\end{bmatrix}$$

Therefore, the conditions for local motor transparency are

$$Z_h(s)\to\infty \quad \text{and} \quad Z_{to}(s)sX_{ref}(s)=F_{ref}(s) \tag{12}$$

Similarly, we derived the conditions for remote motor transparency according to $Q_e(s)=Q_{ref}(s)$

$$\frac{h_{21}(s)}{1-h_{22}(s)Z_e(s)}\cdot\frac{Z_h(s)}{Z_h(s)+Z_{to}(s)}=1 \tag{13}$$

$$Z_e(s)sX_{ref}(s)=F_{ref}(s) \tag{14}$$

Likewise, we derived the conditions for the force control strategy in Fig. 1B, the results of which are summarized in Table 1.

3.2 Transparentizing

In this subsection we show that our main hypothesis, that it is possible to achieve perceptual and remote transparency without local motor transparency, is supported by our linear analysis.

Consider the case of perceptual underestimation of delayed stiffness (as happens when subjects probe spring-like fields without leaving them, i.e. linear conditions). If we set $Z_{to}(s)=Z_e(s)+\Delta K/s$, where ΔK is the perceptual shift we can correct for this underestimation and achieve perceptual transparency.

Let us examine the case of position control (first row of Table 1). If we set

$$\frac{h_{21}(s)}{1-h_{22}(s)Z_e(s)}=1 \tag{15}$$

and the operator increases its impedance such that

$$Z_h(s)\to\infty \tag{16}$$

and we follow the physical constraint on transparency

$$Z_e(s)sX_{ref}(s)=F_{ref}(s) \tag{17}$$

by selecting feasible reference trajectory, then we ensure remote transparency. Note that we still have the flexibility to demand perceptual transparency by selecting the H-matrix parameters according to:

$$\begin{aligned}Z_{to}(s)=Z_e(s)+\frac{\Delta K}{s}&=h_{11}(s)+h_{12}(s)Z_e(s)\\h_{11}(s)&=Z_e(s)\left[1-h_{12}(s)\right]+\frac{\Delta K}{s}\end{aligned} \tag{18}$$

However, the cost of this demand is that $Z_{to}(s)\neq Z_e(s)$, and therefore, the condition for local motor transparency cannot be satisfied. This is exactly the essence of our main hypothesis.

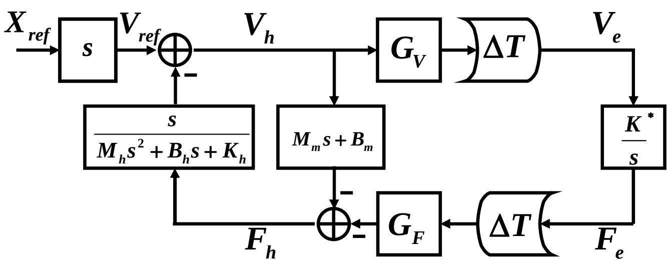

Figure 2: The simulated scenario. See text for detailed description of individual blocks

4. SIMULATION OF TRANSPARENTIZING

In the previous section transparentizing was demonstrated to be possible theoretically; namely the conditions for perceptual and remote transparencies were derived for ideal system. The delay was not considered. However, in practice condition (15) cannot be satisfied with a causal system online. In addition, condition (16) is unachievable, since one cannot create infinite impedance using natural human grip. In this section we simulate the process of transparentizing in a more realistic system, depicted in Fig. 2.

This system resembles the virtual reality scenario in our psychophysical studies of perception of delayed stiffness using wrist movements [14, 15, 18], and therefore we will be able to draw conclusions about the connection between simulated and experimental results.

We modeled the human operator as a linear time invariant (LTI) second order mechanical system, i.e. $Z_h(s) = M_h s + B_h + \frac{K_h}{s}$. Such approximation for human hand impedance is very common [23-25] and provides a reasonable approximation for short movements around a working point. We used wrist parameters similar to [25].

The human operator interacts with a haptic device, the master robot, which was modeled as LTI mass-damper system, i.e. $h_{11}(s) = -Z_m(s) = -(M_m s + B_s)$. This approximation is widely used in the literature [3, 23, 26], and it is especially appropriate for describing the Phantom Desktop haptic device used in our psychophysical studies [14, 15, 18]. For simplicity, at this stage we assume ideal dynamics for the slave robot, i.e. $h_{22}(s) = 0$. Table 2 specifies all the system parameters used in our simulation. We assume a simple transmission line consisting of a gain and a delay, i.e. $h_{21}(s) = G_V e^{-sT}; h_{12}(s) = -G_F e^{-sT}$, where the total transmission gain is unity, i.e. $G_V = 1/G_F$, as the gain in scaled teleoperation, cf. [4, 6].

The modeled environment is a one-sided spring, i.e.

$$f_e(t) = \max(K(x_e(t) - x_0), 0) \qquad (19)$$

where x_0 is the spring's boundary, and K is its stiffness. We modeled this environment as a linear spring followed by a saturation block. The asterisk superscript near K in Fig. 2, indicates that this is not a linear spring but a one-sided spring as described above.

Table 2: Simulated system parameters

Parameter	*Symbol*	*Value (units)*
Wrist mass	M_h	0.15 (kg)
Wrist damping	B_h	5 (Ns/m)
Wrist stiffness	K_h	500 (N/m)
Manipulator mass	M_m	0.045 (kg)
Manipulator damping	B_m	0.01 (Ns/m)
Environment stiffness	K	145 (N/m)
One-way delay	ΔT	0.005 – 0.05 (s)

We simulated the trajectory of reversal (slicing) movements to a target located 0.009m inside the spring-like force field. We constructed the input hand trajectory ($x_{ref}(t)$) by concatenating two fifth order polynomial representing two reaching movements to and from the target as derived by minimizing

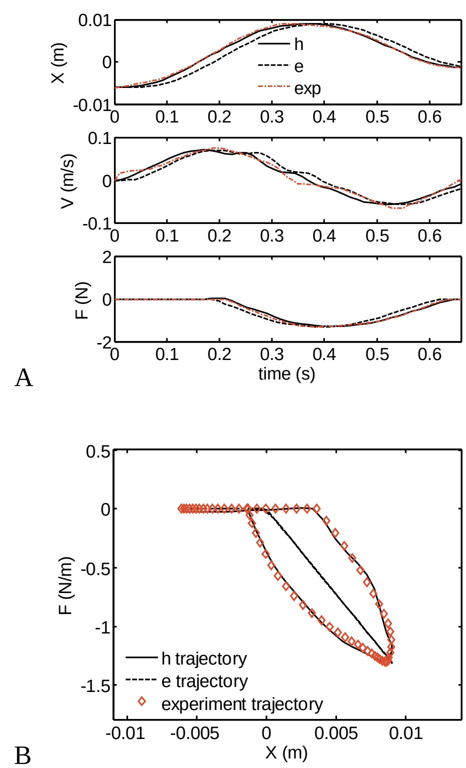

Figure 3: A. Simulated (solid and dashed) and experimental (dot-dashed) trajectories. In the simulated trajectories h and e stand for hand and environment. In the experimental results only the hand trajectory is depicted since the environment was simulated using virtual reality software (see [18] for details). B Trajectories in Force-Position plane.

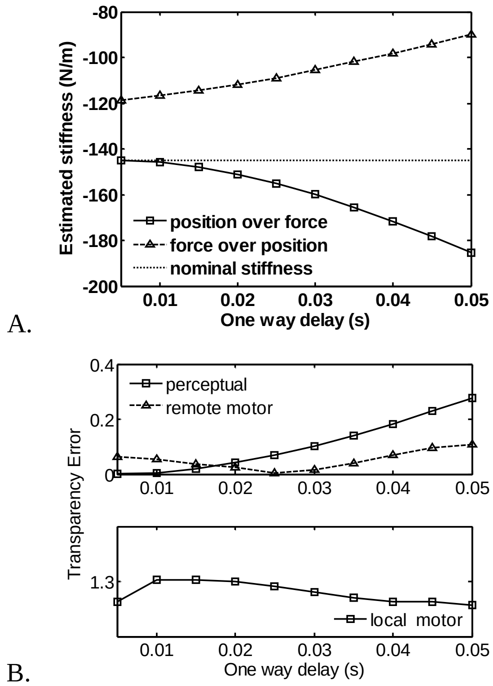

Figure 4: A The influence of delay on the perceptual distortion, according to simulation with unit force and velocity gain (G_F=G_V=1). Perception was calculated according to the components of Eq. (3), namely, $\hat{K}_{PF}$, $\hat{K}_{FP}$ - estimation of stiffness by regression of position over force, and force over position, respectively. B. The influence of delay on perceptual, remote and local motor transparency error, according to the same simulation.

the jerk [27]. Experimental studies showed that this is a reasonable approximation for a slicing movement without force field [28, 29]. Due to interaction with the channel and the remote object, the resultant hand trajectory was different, as depicted in Fig. 3, however it resembled the trajectories we observed in our experiments [15, 18], reinforcing our assumptions about the reference trajectory.

The slicing task was selected for simplicity, as it is based on only one point relevant for the motor measure of transparency – the reversal point. Namely, the movement is considered remotely transparent when the penetration into the environment spring-like surface is exactly 0.009m. Thus, with Euclidian norm and the choice C=1 Eq. (6) is reduced to.

$$MTE_R = \sqrt{\left(x_{rev} - 0.009\right)^2 + \left(f_{rev} - 0.009 \cdot K\right)^2} \quad , \qquad (20)$$

where x_{rev} and f_{rev} are position and force at reversal. We first examined the effect of delay on the simulated system without force or velocity gain (G_V=G_f=1), with input hand trajectory of slicing movement between x_h=-0.006m and x_h=0.0067, and back to x_h=-0.0014m. In these conditions the two components of Eq. (9), regression models PF and FP yield overestimation and underestimation of stiffness respectively (Fig. 4A). The distortion increased with increasing delay. Here we simulated a single movement, completed outside the field, and therefore there was one boundary crossing and one movement, namely $\alpha = 1$ in Eq. (9). Therefore, MTE_P increased as well with increasing delay (Fig. 4B). In addition, both motor transparency errors were affected by delay. With the particular simulated motor command and target the best remote motor transparency is at one way delay of 25ms, but it can be changed slightly by changing the amplitude and starting point of the reference trajectory command.

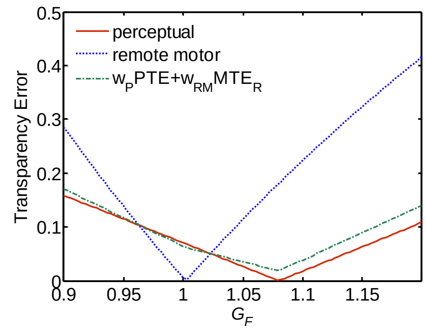

Figure 5: Changing the value of velocity and force gain (G_V=1/G_F) leads to perceptual and remote transparency. Here we used w_P=0.9 and w_{rm}=0.1. The choice of the weights should be task related.

In Fig. 5 the perceptual and the remote motor transparency errors are depicted as a function of the gain for one-way delay of 25ms. By changing the velocity and force gain (keeping the total loop gain at unity) one can select the desired combination of transparencies. The minima for PTE and MTE_R aren't necessarily at the same gain value, and therefore one can use the weights w_P and w_{RM} to find the optimal gain, according to the task demand. Clearly, this optimal gain level is specific for the chosen delay, gain, and input trajectory. Changing the delay will increase the remote motor transparency error. The total transparency error could be further minimized by changing the reference trajectory, which could bring the minima to the same location. However, the reference trajectory is not part of the channel, and this requires training of the human operator.

5. DISCUSSION

We defined a new multidimensional measure for transparency. This measure includes perceptual, local motor, and remote motor transparency components. We then proposed a transparentizing process in which the perceptual as well as the remote transparency errors are minimized, possibly by sacrificing the local motor transparency. We have demonstrated the feasibility of this transparentizing process theoretically, and by means of simulation.

Previous measures of transparency considered the channel [3, 4, 6, 7], the operator perception thresholds [10] and frequency dependent sensitivity of the transmitted impedance to changes in the environmental impedance [5, 11]. In this study we propose a measure for transparency, as well as transparentizing process, taking into account the channel and the human operator in the same framework. In addition, our proposed perceptual transparency error takes into account the bias in perception due to delay, which is important for operator skills transfer from direct operation (i.e. non-delayed, ideal channel) to delayed teleoperation and back, and between different delays.

In section 2.2 we defined the perceptual transparency error only for the local human operator since we assumed that the remote side is passive. However, in applications to telerehabilitation or other cases in which the remote side is also operated by human operator, one should also consider the remote perceptual transparency, and extend the theory accordingly.

Future studies are required to consider the specific definition of the motor transparency errors defined here for the first time without considering the detailed tradeoffs in the selection of the metric. Moreover, the human factor constraints over the local motor transparency error in Eq. (9) should be formulated. Future studies should also consider possible training paradigms for the human operator, which may affect both transparencies, and therefore the optimal channel parameters.

Transparentizing teleoperation system is a daunting challenge which 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.

6. ACKNOWLEDGMENTS

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