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Transparency in Time for Teleoperation Systems

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Abstract—**This paper proposes defining transparency in the time domain and establishes a quantitative measure of how the human operator "feels" the remote system in a teleoperation system. The main advantage of the proposed definition and measure of transparency with respect to the other ones is that they allow analyzing the effect of the time-varying delay and remote nonlinear systems on the system transparency. Some examples are analyzed showing how the transparency can be calculated in different time instants for teleoperation systems.**

***Index Terms*—nonlinear systems, teleoperation, time-varying delay, transparency.**

I. Introduction

THE teleoperation systems allow human operators to execute tasks in remote or hazardous environments, and have several types of applications, including telemedicine, exploration, entertainment, tele-manufacturing, and many more [3]. In general, teleoperation systems consist of a local site, where a human operator drives a hand-controller device; a remote site, where a system, as for example a robot, interacts with the physical world; and a communication channel that links both sites [16]. The possibility of interchanging data on tactile and motion information could allow a real sense of tele-presence, with capability of executing a physical work at distance. However, the presence of time delay may induce poor performance and low transparency of a teleoperation system [2], [4], [6], [17]. From this, the design of a control scheme for delayed teleoperation systems should analyze the stability using a mathematical tool [7], [10], [15], [18] as well as the transparency [5], [9]. Currently, there are several control schemes proposed for teleoperation systems such as [1], [11], [12], [13],[19],[20],[21],[22]; where stability and transparency are opposed characteristics [2], [9].

In the current literature, transparency is defined as the impedance felt by the human operator on the local site, and it is based on the frequency domain [9]. Such definition can not be applied to remote nonlinear systems and the time-varying delay is not considered.

This paper proposes defining and quantitatively measuring the transparency of a teleoperation system in the time domain. We define transparency as the difference between the remote system and the system that the human "feels", described by an equivalent system attached to him such that it interacts with the human in the same way as the remote system. Our definition includes a gain to set the relative importance between the time notion and the system structure "felt" by the human and a non-linear mapping that considers the distortion and the information loss caused by the time-varying delay.

In addition, several examples where the transparency in the time domain is calculated including non-linear systems and time-varying delay are analyzed.

The paper is organized as follows: section II gives the notation used in this paper. In section III, teleoperation systems are described. In section IV, some background material about transparency is introduced. In Section V, a definition and quantitative measure of transparency in the time domain is proposed. Section VI shows some examples of teleoperation systems where the transparency is calculated. Finally, the conclusions of this paper are given in section VII.

II. Notation

In this paper, the following notation is used: $|\mathbf{x}|$ is the Euclidean norm of the vector $\mathbf{x}$, while $\mathbf{x}[\theta_1,\theta_2]$ belongs to the Banach space called C of n-dimensional continuous functions defined between the time instants θ_1 and θ_2 by $\mathbf{x}(\psi)$ for $\psi \in [\theta_1,\theta_2]$ with $\theta_2 > \theta_1$. On the other hand, the induced norm of the function $\dot{\mathbf{x}} = \mathrm{f}(\mathbf{x},\mathbf{u})$ with $\mathrm{f}:\Re^n \times \Re^p \to \Re^n$, where $\mathbf{x} \in \Re^n$, $\mathbf{u} \in \Re^p$, is defined as $|\mathrm{f}| = \sup \frac{|(\mathrm{f}(\mathbf{x}_1,\mathbf{u}_1) - \mathrm{f}(\mathbf{x}_2,\mathbf{u}_2))|}{|[\mathbf{x}_1 \quad \mathbf{u}_1] - [\mathbf{x}_2 \quad \mathbf{u}_2]|}$ $\forall \mathbf{x_1}, \mathbf{x_2} \in \Re^n$ and $\forall \mathbf{u}_1, \mathbf{u}_2 \in \Re^p$, such that $[\mathbf{x}_1 \quad \mathbf{u}_1] - [\mathbf{x}_2 \quad \mathbf{u}_2] \neq \mathbf{0}$ with n and p positive integer numbers. Similarly, if a function $\mathrm{g}:\Re^n \to \Re^m$ is given, the induced norm is defined as $|\mathrm{g}| = \sup \frac{|(\mathrm{g}(\mathbf{x}_1) - \mathrm{g}(\mathbf{x}_2))|}{|\mathbf{x}_1 - \mathbf{x}_2|}$ $\forall \mathbf{x}_1, \mathbf{x}_2 \in \Re^n$ such that $\mathbf{x}_1 - \mathbf{x}_2 \neq \mathbf{0}$.

III. Teleoperation Systems

This section describes the analyzed teleoperation systems that include a human operator driving a remote system (for example a manipulator robot or mobile robot) by means of reference commands sent to it and simultaneously receiving feedback from the remote system, which is linked with the human through a communication channel.

Fig. 1 shows a general diagram of a teleoperation system, where the main signals of the system are the state $\mathbf{x}_r$ of the remote system, the reference command $\mathbf{u}_r$ applied to the remote system, the command $\mathbf{u}_l$ generated by the human operator, the output $\mathbf{y}_r$ of the remote system, and the feedback $\mathbf{y}_l$ perceived by the human operator.

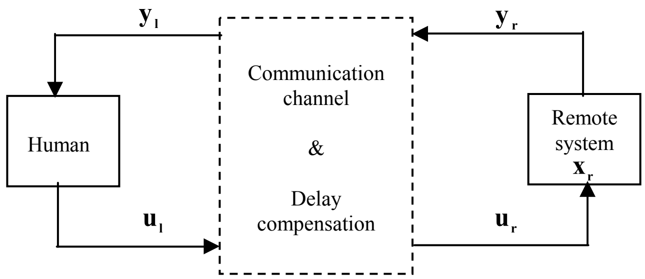

Fig. 1. Teleoperation system

The remote system is described by a linear or non-linear system represented in state space as,

$$\dot{\mathbf{x}}_r(t) = f_r(\mathbf{x}_r(t), \mathbf{u}_r(t)) \quad (1)$$

$$\mathbf{y}_r(t) = g_r(\mathbf{x}_r(t)) \quad (2)$$

Where $\mathbf{x}_r \in \Re^n$, $\mathbf{u}_r \in \Re^p$, $\mathbf{y}_r \in \Re^m$, $f_r : \Re^n \times \Re^p \to \Re^n$, $g_r : \Re^n \to \Re^m$ and $t \in \Re^+$ represents time. We remark that the model of the remote system generally includes some controller.

On the other hand, the communication channel adds time delay and the delay compensation generally modifies the signals sent and received through the communication channel.

IV. BACKGROUND ABOUT TRANSPARENCY

The teleoperation systems search that the human operator is linked as close as it is possible to the remote task. Ideally, the teleoperation must be completely transparent in order that the human feels a direct interaction with the remote task [14].

The papers analyzing transparency are based on describing the teleoperation system by a two-port model with the following hybrid matrix formulation [5], [14],

$$\begin{bmatrix} \mathbf{u}_l \\ \mathbf{y}_l \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} \mathbf{y}_r \\ \mathbf{u}_r \end{bmatrix} , \quad (3)$$

Where $H_{11}(s)$, $H_{12}(s)$, $H_{21}(s)$, $H_{22}(s)$ are transference functions in the domain s of Laplace.

A perfect transparency requires that the impedance felt by the human operator is like the impedance of the remote system. This condition is satisfied if [9]:

$$\begin{cases} H_{22} = 0 \\ H_{21} H_{12}^{-1} = 1 \\ H_{11} = 0 \end{cases} \quad (4)$$

Here, the transparency is defined on the frequency domain using Laplace applied to remote linear systems with constant time delay.

V. TRANSPARENCY DEFINITION AND QUANTITATIVE MEASURE IN THE TIME DOMAIN

The transparency of a teleoperation system indicates a measure of how the human "feels" the remote system. In addition, the transparency gives an idea of how much the human controls the remote system; since the inclusion of delays, and control schemes makes that the human "takes smaller part" compared with a non-delayed direct teleoperation. In this section, we propose a definition of transparency in time and how it can be measured.

A. Equivalent system attached to the human operator

We define an equivalent system attached to the human such that it interacts with the human in the same way as the remote system. Fig. 2 shows how the equivalent system is placed together with the human.

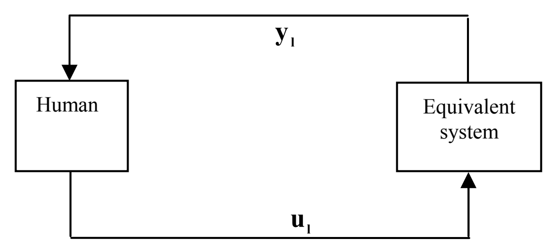

Fig. 2. Equivalent teleoperation system

The equivalent system is defined so that the teleoperation system can be represented by,

$$\mathbf{x}_r(t') = f_r'(\mathbf{x}_r[\theta', t'], \mathbf{u}_l(t)) \quad (5)$$

$$\mathbf{y}_l(t) = g_r'(\mathbf{x}_r[\theta'', t'']) \quad (6)$$

where $f_r' : C \times \Re^p \to \Re^n$, $g_r' : C \to \Re^m$, $\mathbf{u}_l \in \Re^p$, $\mathbf{y}_l \in \Re^m$ and t, t', t'' represent time instants, where we remark that t points to the time instant that the human "lives". The communication channel generally modifies the time intervals $[\theta', t']$ and $[\theta'', t'']$, while the delay compensation generally changes the functions f_r' and g_r'. There is no restriction about $[\theta', t']$, $[\theta'', t'']$ and f_r', g_r'; therefore, the equivalent system can be written "carrying" the feedback from the remote system to the human and "sending back" the remotely applied command to the human.

B. Ideal transparency

The ideal transparency is achieved if $\mathbf{u_l} = \mathbf{u_r}$ and $\mathbf{y_l} = \mathbf{y_r}$ (Fig. 1), which implies that the remote system described by (1) and (2) and the equivalent system given by (5) and (6) verify the following condition,

$$\begin{aligned} f_r' &= f_r \\ g_r' &= g_r \\ t' &= t'' = t \\ \theta' &= \theta'' = t \end{aligned} \quad (7)$$

which implies that the human "feels" the remote system as it is.

C. Transparency in time

We define and measure transparency in the time domain based on "carrying" the remote system felt by the human to the ideal transparency system accumulating the structural changes and the ones in time to reach this. This paper defines the transparency vector $\overline{\mathbf{T_k}} \in \Re^3$ of a teleoperation system represented by (5) and (6), as follows,

$$\overline{\mathbf{T_k}} := (1-k)\left(\left|f_{r_z} - f_{r_z}'\right|\overline{\mathbf{u}} + \left|g_{r_z} - g_{r_z}'\right|\overline{\mathbf{v}}\right) + k\left(\left|t - t^*\right|_t\right)\overline{\mathbf{w}} \quad (8)$$

where $0 \le k \le 1$ defines the relative importance between the time notion and the system structure "felt" by the human, $\overline{\mathbf{u}}, \overline{\mathbf{v}}, \overline{\mathbf{w}}$ are orthogonal vectors among each other, the norms $\left|f_{r_z} - f_{r_z}'\right|$ and $\left|g_{r_z} - g_{r_z}'\right|$ represent the differences between the structure of the remote system and the structure perceived by the human and $\left|t - t^*\right|_t$ considers the time notion perceived by the human. The mentioned norms will be defined later.

Fig. 3 shows a graphical representation of the transparency vector defined in the time domain, where the origin corresponds to ideal transparency and, the higher the Euclidean norm of $\overline{\mathbf{T_k}}$ is, the lower the transparency will be. Therefore, a quantitative measure about the transparency of a teleoperation system is obtained from the norm of the vector $\overline{\mathbf{T_k}}$ defined in (8).

Now, we define $\left|f_{r_z} - f_{r_z}'\right|$ and $\left|g_{r_z} - g_{r_z}'\right|$ as,

$$\left|f_{r_z} - f_{r_z}'\right| := \int_{t-(t'-\theta')}^{t} \left| f_{r_z}(\mathbf{x_r}(\tau), \mathbf{u_l}(t)) - f_{r_z}'(\mathbf{x_r}(\tau - t + t'), \mathbf{u_l}(t)) \right| d\tau \quad (9)$$

$$\left|g_{r_z} - g_{r_z}'\right| := \int_{t-(t''-\theta'')}^{t} \left| g_{r_z}(\mathbf{x_r}(\tau)) - g_{r_z}'(\mathbf{x_r}(\tau - t + t'')) \right| d\tau \quad (10)$$

where the functions $f_{r_z} : \Re^n \times \Re^p \to \Re^n$, $f_{r_z}' : \Re^n \times \Re^p \to \Re^n$, $g_{r_z} : \Re^n \to \Re^m$ and $g_{r_z}' : \Re^n \to \Re^m$ represent the terms of f_r, f_r', g_r, g_r' that depend on the time instants indicated in the arguments of the respective functions. The norms $\left|f_{r_z} - f_{r_z}'\right|$ and $\left|g_{r_z} - g_{r_z}'\right|$ are obtained by comparing the part of the remote system structure with the part of the equivalent system structure that depend on time instants relative to t for f_r, g_r and relative to t' and t'' for f_r' and g_r', respectively.

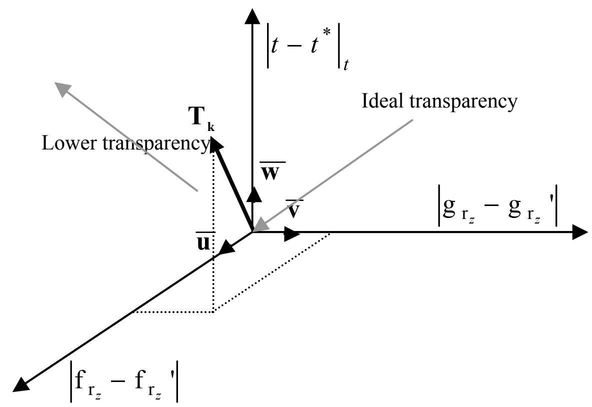

Fig. 3. Transparency vector.

The norm value $\left|t - t^*\right|_t$ depends on the current time instant and it is defined as follows,

$$\left|t - t^*\right|_t := |t' - t''| + |t' - \theta'| + |t'' - \theta''| + \max_{\phi \in [\min(\theta', \theta'') - t, \max(t', t'') - t]} f_w\left(\frac{d|\phi|}{dt}\right) \quad (11)$$

The first term on the right hand considers the loss of transparency depending on the magnitude of the time delay, the second and third ones generally appear due to the dynamics added by the delay compensation, and the last one takes into account the signal distortion (compression and expansion) and the information loss caused by the time-varying delay.

How the function $f_w(\cdot)$ must be? In order to solve this, let us make an analogy between the time-varying delay added by a communication channel where data are transmitted and a tube with variable length where there are numbered balls, infinitesimally separated, traveling at speed v. First, if for a time instant the tube length is incremented faster than the balls speed v, then no balls will come out by the tube in such moment. Second, if the tube length is decreased faster than the balls speed, then some balls will be omitted. Both cases included information loss. Analogically we can talk about position in time of the transmitted signals instead of physical position of the balls; therefore, if the time displacement caused by the time delay varies faster than the speed of time, then there will be information loss.

From this, we define $f_w(\cdot)$ in the following way:

$$f_w\left(\frac{d|\phi|}{dt}\right) := \begin{cases} \dfrac{\frac{d|\phi|}{dt}}{\frac{\frac{d|\phi|}{dt}}{\left|\frac{d|\phi|}{dt}\right|} - \frac{d|\phi|}{dt}} & if \quad 0 \le \left|\frac{d|\phi|}{dt}\right| < 1-\varepsilon \\ \dfrac{1-\varepsilon}{\varepsilon} & if \quad \left|\frac{d|\phi|}{dt}\right| \ge 1-\varepsilon \end{cases} \quad (12)$$

Where $\varepsilon \to 0^+$. Fig. 4 shows how $f_w(\cdot)$ varies depending on the $\frac{d|\phi|}{dt}$.

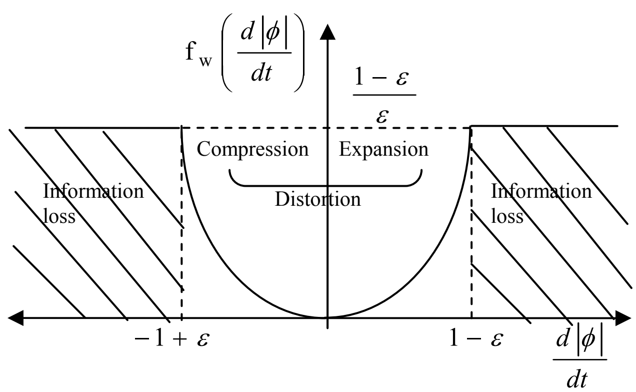

Fig. 4. Function $f_w(\cdot)$.

<u>Remark:</u> Instead of using $\left|t-t^*\right|_t$ in (8), the transparency measure could use the maximum value of $\left|t-t^*\right|_t$ for all t or the average value.

From the proposed definition of the transparency vector $\overline{\mathbf{T}}_\mathbf{k}$, its Euclidean norm gives a measure of the instantaneous transparency where the transparency is higher as $\left|\overline{\mathbf{T}}_\mathbf{k}\right|$ is lower. The limit cases are described by $\left|\overline{\mathbf{T}}_\mathbf{k}\right| = 0$ for ideal transparency and $\left|\overline{\mathbf{T}}_\mathbf{k}\right| \to \infty$ for null transparency.

VI. Examples

A. Example 1

In the first example, we analyze the transparency in time of a delayed teleoperation system without delay compensation. Let us suppose that the remote system is represented by (1) and (2) and that there is a time delay $h(t)$ from the remote system to the human as well as from the human to the remote system. Next, the equivalent system can be represented by,

$$\dot{\mathbf{x}}_\mathbf{r}(t+h) = f_r(\mathbf{x}_\mathbf{r}(t+h), \mathbf{u}_\mathbf{l}(t)) \quad (13)$$

$$\mathbf{y}_\mathbf{l}(t) = g_r(\mathbf{x}_\mathbf{r}(t-h)) \quad (14)$$

where $t' = \theta' = t+h$, and $t'' = \theta'' = t-h$. From (1), (2), (13), (14), we can deduce that $\left|f_{r_z} - f_{r_z}'\right| = 0$, $\left|g_{r_z} - g_{r_z}'\right| = 0$ and $\left|t-t^*\right|_t = 2h(t) + f_w(\dot{h}(t))$. Therefore, the quantitative measure for transparency is given by,

$$\left|\overline{\mathbf{T}}_\mathbf{k}\right| = k\left(2h(t) + f_w\left(\dot{h}(t)\right)\right) \quad (15)$$

The transparency calculated in (15) shows that if the magnitude and derivative of the time delay are higher, then the transparency will be lower (higher norm of the vector $\left|\overline{\mathbf{T}}_\mathbf{k}\right|$).

B. Example 2

Let us suppose that there is a teleoperation system where a human operator drives a joystick-type remote device. Fig. 5 shows a diagram of the teleoperation system which includes delay compensation and a proportional controller attached to the remote device. The communication channel adds a time delay $h_1(t) = 0.1t^2 \ s$ from the remote system to the human and a time delay $h_2(t) = 0.5 \ s$ from the human to the remote system. In addition, the remote device interacts with an elastic remote environment and they are described by,

$$\tau - \tau_e = i\ddot{\vartheta} + b\dot{\vartheta} + mgl\sin\vartheta \quad (16)$$

$$\tau_e = K_e\vartheta \quad (17)$$

Where $l = 0.15m$, $b = 0.02 \ kg.m^2/s$, $i = 0.0041 \ kg.m^2$ and $m = 0.1825kg$ are the length, the friction, inertia and the mass of the joystick [8], while $g = 9.8 \ m/s^2$ is the gravity acceleration, τ is the motor par, τ_e is the par caused by the elastic environment, $K_e = 0.01N.m/rad$ is the elastic constant of the environment, and $\vartheta, \dot{\vartheta}, \ddot{\vartheta}$ are the angular position, velocity and acceleration of the end point of the remote device.

Now, we represent the remote system given by (16) and (17) in state space as follows,

$$\dot{\mathbf{x}}_{\mathbf{r}}(t)=\begin{bmatrix}\dot{x}_{r_1}\\ \dot{x}_{r_2}\end{bmatrix}= \begin{bmatrix} x_{r_2}(t) \\ -\frac{b}{i}x_{r_2}(t)-\frac{mgl}{i}\sin x_{r_1}(t)+\frac{1}{i}\left(K\left(\mathbf{u_r}(t)-x_{r_1}(t)\right)-K_e x_{r_1}(t)\right)\end{bmatrix} \quad (18)$$

$$\mathbf{y_r}(t)=K_e x_{r_1}(t) \quad (19)$$

Where K_p is the parameter of the controller and the state variables are defined as $x_{r_1}=\vartheta$ and $x_{r_2}=\dot{\vartheta}$.

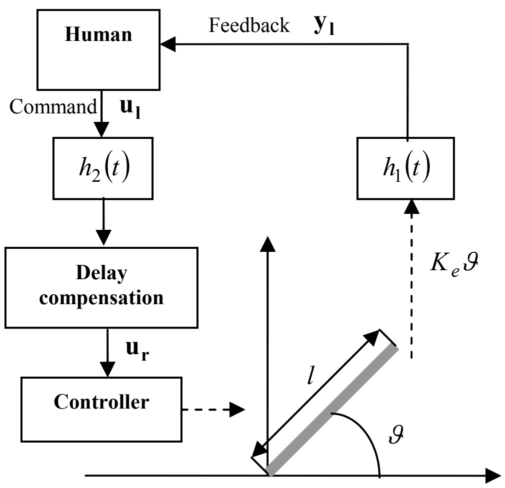

Fig. 5. Teleoperation of a remote device.

We add the stable control scheme proposed in [21] to test the measurement of transparency. Such scheme includes a compensation of the command generated by the human operator without modifying the information feedback sent to the human operator and it is described by,

$$\dot{\mathbf{x}}_{\mathbf{r}}(t)=\mathrm{f_r}\left(\mathbf{x_r}(t),\mathbf{u_l}(t-h_2(t))+\mathbf{C_0x_0}(t)-\mathbf{C_0x_0}(t-h_1(t)-h_2(t))\right) \quad (20)$$

$$\dot{\mathbf{x}}_{\mathbf{0}}(t)=\mathbf{A_0x_0}(t)+\mathbf{B_0y_r}(t) \quad (21)$$

$$\mathbf{y_l}(t)=\mathrm{g_r}\left(\mathbf{x_r}(t-h_1(t))\right) \quad (22)$$

Where the matrices $\mathbf{A_0},\mathbf{B_0},\mathbf{C_0}$ are added by the delay compensation and represent a model of the local site including the human operator. Such matrices are set to [21]:

$$\mathbf{A_0}=\begin{bmatrix}-14 & -2.5\\ 16 & 0\end{bmatrix},\ \mathbf{B_0}=\begin{bmatrix}1\\ 0\end{bmatrix},\ \mathbf{C_0}=\begin{bmatrix}0 & 1.25\end{bmatrix} \quad (23)$$

For this case, the internal state $\mathbf{x_0}$ of the delay compensation is not relevant; therefore, the transference function of the sub-system added by the delay compensation can be written considering (23) as,

$$\mathbf{G_0}(s)=\mathbf{C_0}^{\mathbf{T}}(s\mathbf{I}-\mathbf{A_0})^{-1}\mathbf{B_0}=\frac{16}{s^2+56s+8} \quad (24)$$

Where s is the mathematical operator of Laplace. The gain of the delay compensation $\mathbf{G_0}(s)$ in stationary state is $K_0=2$, while the controller is set to $K_p=0.115 N.m/rad$ [21].

From (20), (24) and only considering the gain in stationary state of $\mathbf{G_0}(s)$(24), the command $\mathbf{u_r}$ can be re-written as,

$$\mathbf{u_r}(t)=\mathbf{u_l}(t-h_2)+K_0\left(\mathbf{y_r}(t)-\mathbf{y_r}(t-h_1-h_2)\right) \quad (25)$$

From (18), (19) and (24), we "carried out" the feedback from the remote system to the human and "sent back" the remotely applied command to the human for getting the equivalent system as,

$$\begin{aligned}\dot{x}_{r_1}(t')&=x_{r_2}(t')\\ \dot{x}_{r_2}(t')&=-\frac{b}{i}x_{r_2}(t')-\frac{mgl}{i}\sin x_{r_1}(t')+\frac{1}{i}\Big(K_p\big(\mathbf{u_l}(t)+\\ &K_0K_e\left(x_{r_1}(t')-x_{r_1}(t'-h_1-h_2)\right)-x_{r_1}(t')\big)-K_e x_{r_1}(t')\Big)\end{aligned} \quad (26)$$

$$\mathbf{y_l}(t)=K_e x_{r_1}(t'') \quad (27)$$

Where $t'=t+h_2$, $\theta'=t-h_1$, and $t''=\theta''=t-h_1$.

Next, we can calculate the transparency using the parameters given in this section. From (18) (remote system) and (26) (equivalent system), we can calculate $\left|\mathrm{f_{r_z}}-\mathrm{f_{r_z}}'\right|$ using (9) as,

$$\left|\mathrm{f_{r_z}}-\mathrm{f_{r_z}}'\right|=2\frac{1}{i}K_eK_pK_0= \\ 2\frac{1}{0.0041}0.01(0.115)(2)=1.12 \quad (28)$$

On the other hand, from (19) (remote system) and (27) (equivalent system), we can calculate $\left|\mathrm{g_{r_z}}-\mathrm{g_{r_z}}'\right|$ using (10) as,

$$\left|\mathrm{g_{r_z}}-\mathrm{g_{r_z}}'\right|=0 \quad (29)$$

Next, we calculate $\left|t-t^*\right|_t$ from (11) and (12) for time instants $t_A=1\ s$ and $t_B=4\ s$, where $h_1=0.1s$, $\dot{h}_1=0.2$, $h_2=0.5\ s$, $\dot{h}_2=0$ for case A and $h_1=1.6s$, $\dot{h}_1=0.8$, $h_2=0.5\ s$, $\dot{h}_2=0$ for case B,

$$\left| t - t^* \right|_{t_A} = (1.5 - 0.9) + (0.5 + 0.1) + 0 + \frac{0.2}{1 - 0.2} = 1.45 \quad (30)$$

$$\left| t - t^* \right|_{t_B} = (4.5 - 2.4) + (0.5 + 1.6) + 0 + \frac{0.8}{1 - 0.8} = 8.2 \quad (31)$$

Finally, putting (28), (29), (30) and (31) into (8), we can quantitatively measure the transparency $\left|\mathbf{T_k}\right|$, for different time instants (t_A and t_B) considering $k = 0.5$, as follows,

$$\left|\overline{\mathbf{T}}_{\mathbf{0.5}}\right| = \sqrt{((1-0.5)1.12)^2 + 0 + ((0.5)(1.45))^2} = 0.91 \quad \text{for} \quad t_A$$

$$\left|\overline{\mathbf{T}}_{\mathbf{0.5}}\right| = \sqrt{((1-0.5)1.12)^2 + 0 + ((0.5)(8.2))^2} = 4.13 \quad \text{for} \quad t_B$$

The achieved result shows the quantitative calculus of the transparency for different time instants. This information is useful for the design of control schemes applied to teleoperation systems, since the controllers and delay compensations could be adapted to keep a certain level of transparency.

VII. Conclusions

The analysis and the design of teleoperation systems require considering the stability and transparency of such systems.

This paper defines the transparency in the time domain and proposes a transparency quantitative measure which includes a gain to set the relative importance between the time notion and the system structure "felt" by the human and a non-linear mapping that considers the distortion and the information loss caused by the time-varying delay.

The main differences between the proposed definition and measure of transparency with respect to the other ones are that they allow analyzing the effect of the time-varying delay and remote nonlinear systems on the system transparency. Table 1 shows the main characteristics of transparency in time with respect to the one in frequency.

Transparency in frequency	**Transparency in time**
Impedance that the human feels	System that the human feels
Frequency domain	Time domain
Constant time delay	Constant and variable time delay
Linear remote systems	Linear and nonlinear remote systems
The distortion and the information loss is not considered	The distortion and the information loss is considered

Table 1. Main characteristics of transparency in time.

Examples about the calculus of transparency for different time instants have shown that the transparency measure can be a useful tool to analyze and design controllers and delay compensations applied to teleoperation systems.

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