Quantitative Absolute Transparency for Bilateral Teleoperation of Mobile Robots

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***Abstract*—This paper proposes a new criterion, called absolute transparency, to design control schemes applied to bilateral teleoperation of mobile robots with time-varying delay. The absolute transparency measures how and how fast the human operator and the remote system interact with each other through a teleoperation system. The absolute transparency of different control schemes is analyzed and tested through teleoperation experiments where a human operator drives a mobile robot and receives both visual and force feedback.**

***Index Terms*—Human-Robot Interaction, mobile robot, teleoperation, time-varying delay.**

I. Introduction

TELEOPERATION systems allow human operators to perform tasks in remote environments including many different applications, such as telemedicine, exploration, entertainment, tele-manufacturing, tele-service, aerial vehicles, and many more [1], [2]. In teleoperation systems, a human operator interacts with a remote environment through a machine, typically a robot, in order to do physical work at a distance [3]. The signals between the human operator and the remote system (machine and environment) are exchanged through a communication channel. However, time delay limits the quantity of applications of teleoperation systems, since the operator perceives (visually, haptically, etc.) the interaction between the robot and the environment (objects, people, other robots, etc.) some time later than the actual interaction, and the commands sent by him to the robot are given some time later too. Thus, the presence of time-delay may induce instability or poor performance in a delayed control system [4]–[6].

Numerous control schemes have been proposed for the standard teleoperation between master-slave manipulators [7], such as delay compensation based on transmission of wave variables [8], [9]; tele-programming [10], [11] and supervisory control [3], [12]; predictive display [13], [14]; control based on transparency [15], remote impedance control [16], [17], passivity-based control considering the discrete system [18], among others. In [19] a state-of-art is presented. On the other hand, although various strategies used in teleoperation of manipulators could be used in teleoperation of mobile robots, few papers show experiments with time delay, as for example event-based control [20], control based on passivity [21] and [22], [23]. Besides, most of the schemes present in the literature are based only on a stability analysis. Therefore, the design of new control schemes to increase the performance of the delayed teleoperation systems of mobile robots in order to raise its application in the industry, services, office, and home currently arises as a motivation in this research area.

Although stability and passivity are concepts well defined in teleoperation of mobile robots, the transparency concept seems not to be fully explored. Instead, it should be analyzed in more depth, since it naturally emerges from the interaction between human operator and a robot. The measures of transparency such as the standard transparency [15], [24] and the one based on the ideal response [25] have been designed to bilateral teleoperation of master-slave manipulators systems, but its application to teleoperation of mobile robots with time-varying delay is difficult.

This paper proposes a new definition called absolute transparency applied to bilateral teleoperation systems of mobile robots. This work is inspired in the classical concept of transparency and in an initial study of transparency in the time domain proposed in [26] where possible advantages of an analysis of transparency in the time domain were presented. Absolute transparency allows us to measure how instantaneous and how is the bilateral interaction between a human operator driving a master and a mobile robot navigating in a remote environment. The definition takes into account possible symmetric and asymmetric time-varying delays, the human operator behavior and non-linear systems, and allows measuring the quantity of absolute transparency that a teleoperation system has providing a common ground to compare different teleoperation systems. In addition, the absolute transparency of different control schemes is analyzed and tested from teleoperation experiments of a mobile robot where the human operator receives visual and force feedback.

The paper is organized as follows: Section II describes the notation used in this paper. In Section III, delayed teleoperation systems are presented. In Section IV, the concept of absolute transparency is proposed. In Section V, the absolute transparency of different control schemes is analyzed. Section VI shows an analysis based on experiments of teleoperation of a mobile robot with visual and force feedback to the user. Finally, the conclusions of this paper are given in section VII.

II. Notation

In this paper, the following notation is used: $\Re^+$ represents the positive real numbers, $\Re^i$ represents a real vector space of dimension i, $|\mathbf{x}|$ is the Euclidean norm of vector $\mathbf{x}$, C^n represents an n-dimensional Banach space of continuous functions $\mathbf{x}\left[\theta_1,\theta_2\right]$ defined by $\mathbf{x}\left(\psi\right)$ for $\psi \in \left[\theta_1,\theta_2\right]$ with time variables $\theta_2 > \theta_1$. The induced norm of the function $\dot{\mathbf{x}} = \mathrm{f}\left(\mathbf{x},\mathbf{u}\right)$ with $\mathrm{f}: \Re^n \times \Re^p \rightarrow \Re^n$, 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 $\mathrm{g} : \Re^n \rightarrow \Re^m$ 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 $\mathbf{x_1}-\mathbf{x_2} \neq \mathbf{0}$. Table I shows the nomenclature used in this paper.

TABLE I
NOMENCLATURE.

$\mathbf{x_h}$:	state of the local system
$\mathbf{u_l}$:	command generated by the human operator
$\mathbf{y_l}$:	feedback signals
$\mathbf{x_r}$:	state of the remote system
$\mathbf{u_r}$:	control action or reference command applied to the remote system
$\mathbf{y_r}$:	information back-fed from the remote system
$\mathrm{f_h}, \mathrm{g_h}$:	system represented in state space formed by the human operator and master
$\mathrm{f_r}, \mathrm{g_r}$:	system represented in state space formed by the robot and its environment
$\mathrm{f'_h}, \mathrm{g'_h}$:	local equivalent system represented in state space
$\mathrm{f'_r}, \mathrm{g'_r}$:	remote equivalent system represented in state space
$\mathbf{x_{h_e}}$:	state of the local equivalent system
$\mathbf{x_{r_e}}$:	state of the remote equivalent system
T_t :	instantaneous transparency
T_L :	local transparency
T_R :	remote transparency
$\mathbf{T}$:	vector of absolute transparency

III. Delayed Teleoperation Systems

This section analyzes a teleoperation system that includes a local site, where a human operator drives a remote mobile robot navigating in an environment (e.g. corridor with people). He/she uses some device to generate reference commands which are sent to the robot and simultaneously he/she receives feedback such as force, sound, and video from the remote system, as shown in Fig. 1. The human operator and the remote system are connected through a data communication channel (e.g. Internet).

Fig. 2 shows the general scheme of a teleoperation system. Here, the remote system consists of a mobile robot and its environment. Let us assume that the remote system can be described by a non-linear system represented in state space by,

$$\dot{\mathbf{x}}_\mathbf{r}(t) = \mathrm{f_r}(\mathbf{x_r}(t), \mathbf{u_r}(t)) \tag{1}$$

$$\mathbf{y_r}(t) = \mathrm{g_r}(\mathbf{x_r}(t)) \tag{2}$$

where $\mathbf{x_r} \in \Re^n$ is the state of the remote system, $\mathbf{u_r} \in \Re^p$ is the control action or reference command applied to the remote system, $\mathbf{y_r} \in \Re^m$ represents the information back-fed from the remote system, $\mathrm{f_r} : \Re^n \times \Re^p \to \Re^n$, $\mathrm{g_r} : \Re^n \to \Re^m$ and $t \in \Re^+$ represents time, with n, m, p positive integer numbers.

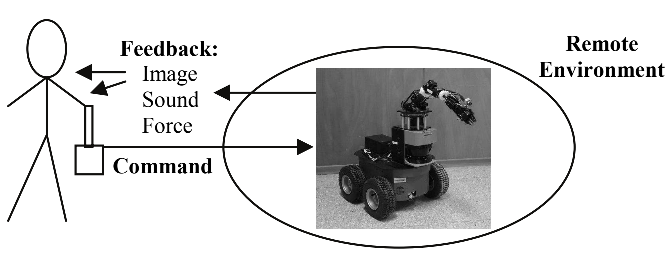

Fig. 1. Teleoperation system.

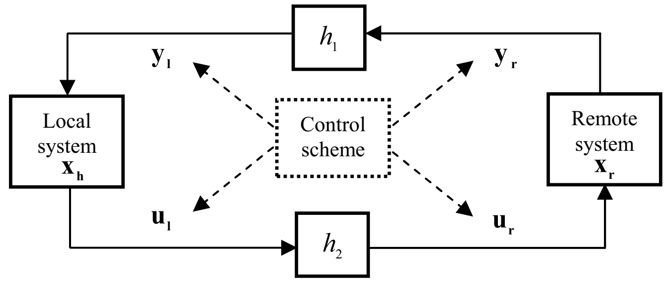

Fig. 2. Control scheme applied to teleoperation systems.

On the other hand, the communication channel adds a time delay h_1 to the signals sent from the remote system to the human operator and a time delay h_2 to the signals sent by the operator using a master to the remote system. In general, information loss could be added by the communication channel used.

In addition, let us consider that the local system, which includes the human operator and master, can be modeled by a linear or non-linear system represented in state space by,

$$\dot{\mathbf{x}}_\mathbf{h}(t) = \mathrm{f_h}(\mathbf{x_h}(t), \mathbf{y_l}(t)) \tag{3}$$

$$\mathbf{u_l}(t) = \mathrm{g_h}(\mathbf{x_h}(t)) \tag{4}$$

where $\mathbf{x_h} \in \Re^k$ is the state of the local system, $\mathbf{u_l} \in \Re^p$ is the command generated by the human operator, $\mathbf{y_l} \in \Re^m$ is the information back-fed to him/her from the remote site, $\mathrm{f_h} : \Re^k \times \Re^m \to \Re^k$, $\mathrm{g_h} : \Re^k \to \Re^p$ and $t \in \Re^+$ represents time, with k a positive integer number.

In general, the master device model can be easily obtained, whereas to model the human operator is a difficult task. Classical papers, as in [27]–[29], represent the human output using quasi-linear models, but some human behavior can be better described using non-linear models [30], [31].

The time delays h_1 and h_2 generally will cause a poor performance of a mobile robot teleoperation system. Therefore, some control scheme must be included in the system to achieve a performance useful in practice. In general, the control schemes applied to teleoperation systems modify the signals sent and received through the communication channel or add simulators to the local site or include a high-level of automation in the remote system. But, a number of questions are open, for example: how can the designer correctly choose the composition of the control scheme of a delayed teleoperation system? How should the designer compare different control schemes? Does the selection of a control scheme depend on the application-type? How should the parameters and structure of each control block of any scheme be set? If the degree of automation of the remote system is higher, e.g. including compliance, hybrid controllers, etc., would the performance of the teleoperation system be higher too? If a teleoperation system is stable in theory, does it necessarily work well in practice? Currently, these questions seem to be only partially addressed in the literature on teleoperation of mobile robots. In order to increase the conceptual tools for trying to solve these inquires, a new method to design and analyze teleoperation systems is proposed, as discussed next.

IV. Absolute Transparency in the Time Domain

This paper proposes a new definition called *absolute transparency*. The absolute transparency attempts to reflect how and how fast the human operator and the remote system interact with each other through a teleoperation system. The proposal establishes a vector in a 3D space identified by a set of base vectors called *local transparency*, *remote transparency* and *instantaneous transparency*. The first two quantify the similarity between the system felt by the human operator and the real remote system and between the system seen from the remote system and the human operator, respectively. The proposed definition allows making such structural comparisons independently of the magnitude of the time delay. The last base vector depends on the current time instant and allows to quantify the master dynamics, the slave dynamics and how fast the human operator and the remote system feel the interaction with the remote system and the local system, respectively, through the teleoperation system.

The proposed definition, based on the time domain and models in state space, allows quantitatively getting the level of absolute transparency that a teleoperation system has. Thus, different control schemes could be compared according to this new criterion.

A. Remote and Local Equivalent Systems

In general, delayed teleoperation systems are described by delayed functional differential equations [32], [33]. Therefore, the comparison between the remote system described by (1), (2) and the local system represented by (3), (4) with the structures felt by each one of them is not direct because the states and dependence in time are different for each of them. We propose a way to compare such systems based on the definition of remote and local equivalent systems, as they are seen from the local system and remote system, respectively (Fig. 3). To compute the remote and local equivalent systems, we force the explicit dependence in time of $\mathbf{u_l}, \mathbf{y_l}$ and $\mathbf{u_r}, \mathbf{y_r}$ to t respectively.

By carrying the feedback from the remote system to the local system in h_1 seconds and by sending back the remotely

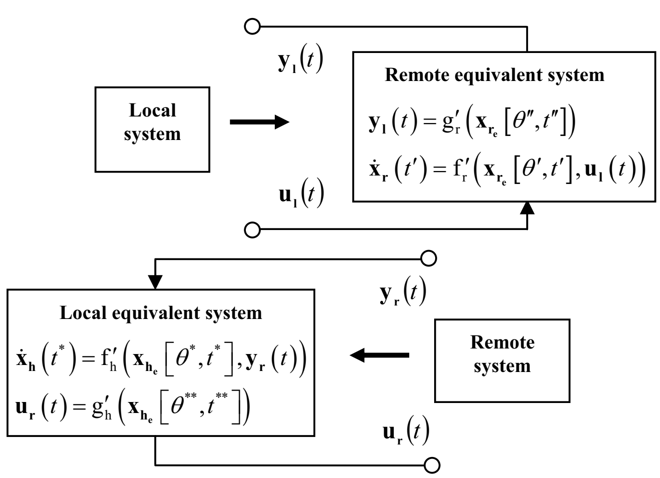

Fig. 3. Local and remote equivalent systems.

applied command to the local system in h_2 seconds (see Fig. 2), the remote equivalent system can be obtained by delayed functional differential equations with a general structure described by,

$$\dot{\mathbf{x}}_\mathbf{r}\left(t'\right) = \mathrm{f}'_\mathrm{r}\left(\mathbf{x}_{\mathbf{r_e}}\left[\theta', t'\right], \mathbf{u_l}\left(t\right)\right) \tag{5}$$

$$\mathbf{y_l}\left(t\right) = \mathrm{g}'_\mathrm{r}\left(\mathbf{x}_{\mathbf{r_e}}\left[\theta'', t''\right]\right) \tag{6}$$

where $\mathrm{f}'_\mathrm{r} : C^{n'} \times \Re^p \to \Re^n$, $\mathrm{g}'_\mathrm{r} : C^{n'} \to \Re^m$, $\mathbf{u_l} \in \Re^p$, $\mathbf{y_l} \in \Re^m$, t', t'', θ', θ'' represent time variables and $\mathbf{x}_{\mathbf{r_e}} \in \Re^{n'}$ with $n' \geq n$, thus $\mathbf{x}_{\mathbf{r_e}}$ has more state variables than $\mathbf{x_r}$.

In non-delayed teleoperation systems, $t = t' = t'' = \theta' = \theta''$ but when there is time delay, $t' = t + h_2$, $\theta'' = t - h_1$, and t'' and θ' depend on the composition of the control scheme and verify $\theta' \leq t'$ and $\theta'' \leq t''$.

In a similar way to the remote equivalent system, the local equivalent system (Fig. 3) can be described as follows,

$$\dot{\mathbf{x}}_\mathbf{h}\left(t^*\right) = \mathrm{f}'_\mathrm{h}\left(\mathbf{x}_{\mathbf{h_e}}\left[\theta^*, t^*\right], \mathbf{y_r}\left(t\right)\right) \tag{7}$$

$$\mathbf{u_r}\left(t\right) = \mathrm{g}'_\mathrm{h}\left(\mathbf{x}_{\mathbf{h_e}}\left[\theta^{**}, t^{**}\right]\right) \tag{8}$$

where $\mathrm{f}'_\mathrm{h} : C^{k'} \times \Re^m \to \Re^k$, $\mathrm{g}'_\mathrm{h} : C^{k'} \to \Re^p$, $\mathbf{u_r} \in \Re^p$, $\mathbf{y_r} \in \Re^m$, t^*, t^{**}, θ^*, θ^{**} describe time variables and $\mathbf{x}_{\mathbf{h_e}} \in \Re^{k'}$ with $k' \geq k$.

In non-delayed teleoperation systems $t = t^* = t^{**} = \theta^* = \theta^{**}$, but for delayed teleoperation systems, $t^* = t + h_1$, $\theta^{**} = t - h_2$ and t^{**} and θ^* depend on the control scheme.

B. Absolute Transparency

This paper defines the absolute transparency of a delayed teleoperation system represented by the local and the remote equivalent system described by (5), (6), (7) and (8) as follows,

$$\mathbf{T} := T_L\bar{\mathbf{u}} + T_R\bar{\mathbf{v}} + k_t T_t\bar{\mathbf{w}} \tag{9}$$

where $\mathbf{T} \in \Re^3$, $\bar{\mathbf{u}}$, $\bar{\mathbf{v}}$, $\bar{\mathbf{w}}$ are orthogonal vectors to each other, T_L is called local transparency, T_R is called remote transparency, $T_t\,[\mathrm{sec}]$ is called instantaneous transparency, where $k_t\left[\frac{1}{\mathrm{sec}}\right]$ is a weight gain.

Fig. 4 shows a graphical representation of the proposed absolute transparency vector, where the origin corresponds to ideal transparency. The limit cases are described by $|\mathbf{T}| = 0$ for ideal absolute transparency and $|\mathbf{T}| \to \infty$ for the worst absolute transparency. Next, the components of the absolute transparency (9) will be defined.

C. Local and Remote Transparencies

The local transparency T_L is defined as the measure of how similar the remote system felt by the human operator driving the master is to the ideal system felt by him/her, i.e. the remote system as it is. The local transparency T_L is computed as the difference between the remote equivalent system described by (5) and (6) and the remote system represented by (1) and (2) in which $\mathbf{u_r}$ and $\mathbf{y_r}$ are replaced for $\mathbf{u_l}$ and $\mathbf{y_l}$, as follows:

$$T_L := \left|\mathrm{f}'_\mathrm{r} - \mathrm{f}_\mathrm{r}\right| + q_l\left|\mathrm{g}'_\mathrm{r} - \mathrm{g}_\mathrm{r}\right| \tag{10}$$

where the terms on the right hand side in (10) are compared considering the time variable t in f_r (1) and g_r (2) similar to

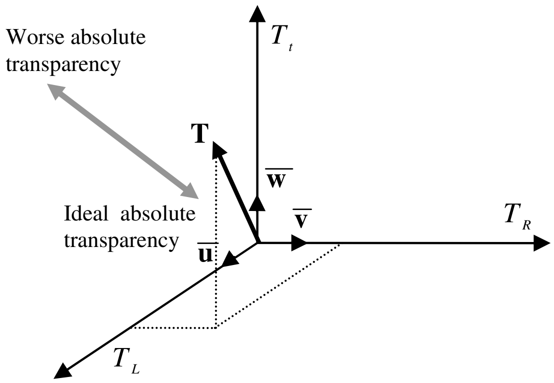

Fig. 4. Absolute transparency vector.

t' and t'' in f'_r (5) and g'_r (6), respectively. The gain $q_l > 0$ is only added to make a better comparison between different physical units.

On the other hand, the remote transparency T_R is defined as a measure of how similar the operator (including the master) felt by the remote system is to the local system, i.e. the ideal system seen from the remote system. The remote transparency T_R is computed as the difference between the local equivalent system described by (7) and (8) and the local system represented by (3) and (4) in which $\mathbf{u_l}$ and $\mathbf{y_l}$ are replaced for $\mathbf{u_r}$ and $\mathbf{y_r}$, as follows:

$$T_R := |\mathrm{f}'_\mathrm{h} - \mathrm{f}_\mathrm{h}| + q_r\, |\mathrm{g}'_\mathrm{h} - \mathrm{g}_\mathrm{h}| \tag{11}$$

where the terms on the right hand side in (11) are compared forcing t in f_h (3) and g_h (4) similar to t^* and t^{**} in f'_h (7) and g'_h (8), respectively. The gain $q_r > 0$ is added for the same use that q_l.

The comparisons made in computing T_L and T_R use the same relative dependence in time respect to the non-delayed time variable (mathematically forcing $t = t' = t'' = t^* = t^{**}$) in order to make a structural comparison independently from the magnitude of the time delay. In addition, the induced norm is applied taking into account that the outputs of two generic systems i and j, represented by the input-state functions $\mathrm{f_i}$ and $\mathrm{f_j}$ and the state-output functions $\mathrm{g_i}$ and $\mathrm{g_j}$, can be compared by $|\mathrm{f_i} - \mathrm{f_j}| + |\mathrm{g_i} - \mathrm{g_j}|$ if they have similar relative dependence in time with respect to their time instants without delay as well as similar dimensional dependence in input, state and output or bounded by $|\mathrm{f_i}| + |\mathrm{f_j}| + |\mathrm{g_i}| + |\mathrm{g_j}|$ otherwise.

D. Instantaneous Transparency

We propose as component of the absolute transparency a time variable that represents the dynamics of the master, the dynamics of the slave, the loss of instantaneity, the apparent delay felt by the human operator and the remote system and the effects of the distortion and information loss produced by the time varying delay. This component is called instantaneous transparency T_t. From a teleoperation system represented by (5), (6), (7) and (8), T_t is defined as follows:

$$\begin{aligned} T_t := {} & |t_{u_a} - t'| + |\theta'' - t| + |t_{y_a} - t^*| + |\theta^{**} - t| + t_m + t_s \\ & + \mathrm{f_w}\left(\tfrac{d|t_{u_a} - t|}{dt}\right) + \mathrm{f_w}\left(\tfrac{d|t' - t|}{dt}\right) + \mathrm{f_w}\left(\tfrac{d|\theta'' - t|}{dt}\right) \\ & + \mathrm{f_w}\left(\tfrac{d|t_{y_a} - t|}{dt}\right) + \mathrm{f_w}\left(\tfrac{d|t^* - t|}{dt}\right) + \mathrm{f_w}\left(\tfrac{d|\theta^{**} - t|}{dt}\right) \end{aligned} \tag{12}$$

The first and second terms and the third and fourth terms represent the apparent delays t_{L_a} and t_{R_a} that the human operator (driving the master) and the remote system feel interacting with their opposite sites.

Let us assume that (5) and (7) can be represented by,

$$\dot{\mathbf{x}}_\mathbf{r}(t') = \mathrm{f_r}(\mathbf{x_r}(t'), \mathbf{u_A}) \tag{13}$$

$$\dot{\mathbf{x}}_\mathbf{h}(t^*) = \mathrm{f_h}(\mathbf{x_h}(t^*), \mathbf{y_A}) \tag{14}$$

where

$$\mathbf{u_A} = \mathbf{u_l}(t) + \mathrm{v_u}(\mathbf{x_{r_e}}[t_{u_d}, t_{u_a}]) \tag{15}$$

with $t_{u_d} \leq t_{u_a}$ and $\mathrm{v_u} : C^{n'} \rightarrow \Re^p$ and

$$\mathbf{y_A} = \mathbf{y_r}(t) + \mathrm{v_y}(\mathbf{x_{h_e}}[t_{y_d}, t_{y_a}]) \tag{16}$$

with $t_{y_d} \leq t_{y_a}$ and $\mathrm{v_y} : C^{k'} \rightarrow \Re^m$.

In case of $\mathrm{v_u} = 0$, t_{u_a} is considered equal to t for the calculus of instantaneous transparency. Similarly, when $\mathrm{y_u} = 0$, we consider $t_{v_y} = t$.

Taking into account (6), (13), (8) and (14), t_{L_a} and t_{R_a} are defined as,

$$t_{L_a} = t'_{L_a} + |\theta'' - t| = |t_{u_a} - t'| + |\theta'' - t| \tag{17}$$

$$t_{R_a} = t'_{R_a} + |\theta^{**} - t| = |t_{y_a} - t^*| + |\theta^{**} - t| \tag{18}$$

The apparent delay t_{L_a} is formed for two time variables. The first one represents the elapsed time between an apparent control action $\mathbf{u_A}$ (15) (composed by the command $\mathbf{u_l}$ but modified by the control scheme) is applied to the remote system, and the time instant in which its state changes due to such action. This change is transmitted to the human operator who feels a feedback signal $\mathbf{y_l}$. The concept of t_{R_a} is similar to t_{L_a} considering an apparent feedback $\mathbf{y_A}$ (16) on the human operator and its path to $\mathbf{u_r}$.

The terms $|\theta'' - t|$ and $|\theta^{**} - t|$ on the right hand side in (12) represents how much time elapses between a variation in the human operator's command ($\mathbf{u_l}$) and its effect on the remote system and how much time elapses between a variation in the output of the remote system ($\mathbf{y_r}$) and its effect on the human operator. These two terms are equals to $h_1 + h_2$ for all control schemes and represent the loss of instantaneity of a delayed teleoperation respect to a non-delayed teleoperation.

The terms t_m and t_s represent the dynamics of the master and slave respectively. Let us assume that the master and slave are stables with bounded input-bounded output. Then, t_m and t_s represent the time constant of a linear system similar in its rate of response with respect to the real ones.

Finally, the last six terms in (12) take into account the signal distortion (compression and expansion) and the information loss caused by the time-varying delay. These terms are described "unilaterally", deduced from the first four "bilateral" terms in (12). Thus, they allow analyzing the information loss

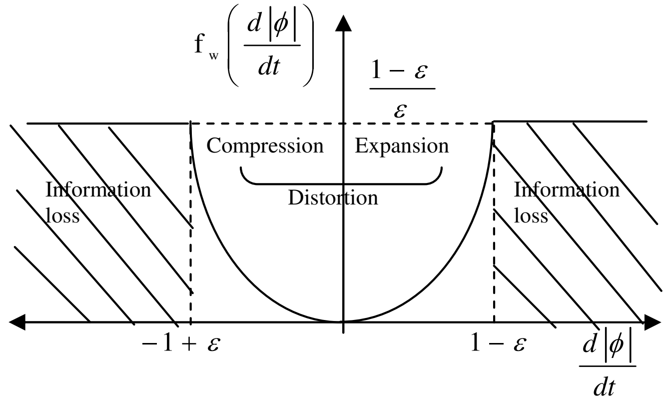

Fig. 5. Function $\mathrm{f_w}(\cdot)$.

and distortion between a transmission point and a reception point. On the other hand, the definition (12) takes into account the variation rate of the time delay too. But, what should the function $\mathrm{f_w}(\cdot)$ be? In order to answer this question, 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. Let us assume that only one ball or data is taken in the output for each time instant. First we note that if at a certain time instant the tube length is incremented faster than the balls speed v, then no ball will come out of the tube at such time. Second, if the tube length is decreased faster than the balls speed, then some balls will be omitted. Both cases include information loss. In an analog way, 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 derivative of the "position in time" $\left(\frac{dh}{dt}>1\right)$, then there will be information loss.

From this, the function $\mathrm{f_w}(\cdot)$ returns a value in seconds for compatibility in (12) defined by [26] as:

$$\mathrm{f_w}\left(\frac{d|\phi|}{dt}\right) := \begin{cases} \frac{\left|\frac{d|\phi|}{dt}\right|}{1-\left|\frac{d|\phi|}{dt}\right|} & \text{if} \quad 0 \leq \left|\frac{d|\phi|}{dt}\right| < 1-\varepsilon \\ \frac{1-\varepsilon}{\varepsilon} & \text{if} \quad \left|\frac{d|\phi|}{dt}\right| \geq 1-\varepsilon \end{cases} \tag{19}$$

where $0<\varepsilon<1$ and ϕ ranges $t_{u_a}-t$, $t'-t$, $\theta''-t$, $t_{y_a}-t$, t^*-t and $\theta^{**}-t$, see (12). Fig. 5 shows how $\mathrm{f_w}(\cdot)$ varies depending on the $\frac{d|\phi|}{dt}$.

The function $\mathrm{f_w}$ takes as argument $\frac{d|\phi|}{dt}$ since it measures the effect of the variation rate of the time delay without considering if the displacement in time is forward or backward respect to t. The value ε is set according to the application establishing a practical bound to $\mathrm{f_w}$ without changing such function until $\varepsilon-1$. In general, ε will be a small value to make $\mathrm{f_w}$ finite and to weigh the distortion (compression and expansion) differently respect to the information loss.

A better instantaneous transparency implies that the human operator and the remote system feel the interaction with each other as fast as possible; this is, if T_t is smaller, then the absolute transparency is better.

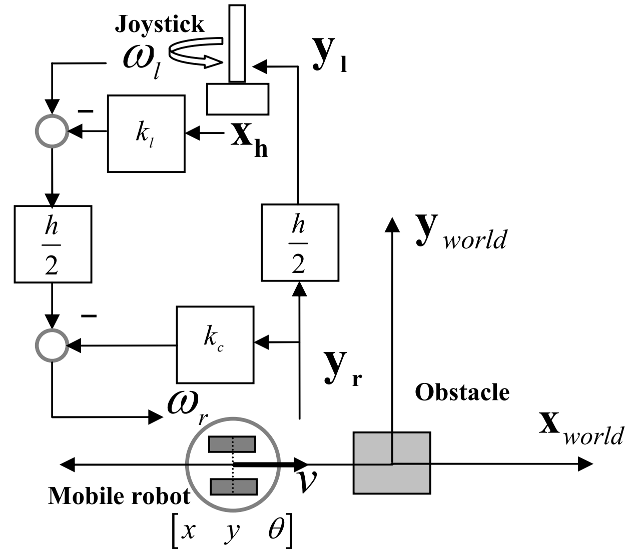

Fig. 6. Teleoperation system of a mobile robot with force feedback.

E. Example

A simple teleoperation system of a mobile robot with force feedback in one DOF is analyzed in order to clarify the proposed concept of absolute transparency. Let us assume that a human operator drives the angular velocity of a mobile robot navigating at constant linear velocity. The user turns a joystick to establish such command receiving a torque feedback simultaneously through a communication channel which adds a constant delay $\frac{h}{2}$ from the robot to the user and vice versa.

The mobile robot can be expressed in Cartesian coordinates by the known classic kinematic model given by:

$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} v\cos\theta(t) \\ v\sin\theta(t) \\ \omega_r(t) \end{bmatrix} \tag{20}$$

where $\mathbf{u_r} = \left[\begin{smallmatrix} v \\ \omega_r \end{smallmatrix}\right]$ is the control action with v the linear velocity and ω_r the angular velocity of the mobile robot, and x, y, θ represent the position and orientation of the mobile robot respect to a reference frame.

The environment is modeled by a torque generated by the interaction between the mobile robot and the obstacles around it. The torque $\mathbf{y_r}$ is computed as,

$$\mathbf{y_r}(t) = k_f\left(D - \sqrt{x(t)^2 + y(t)^2}\right) \tag{21}$$

for $D \geq \sqrt{x^2+y^2}$ and $\mathbf{y_r}=0$ otherwise.

The obstacle is placed on the origin of the reference frame (Fig. 6), $D\,[m]$ establishes the maximum distance of detection, and $k_f\left[\frac{Nm}{m}\right]$ converts the distance between the mobile robot and the obstacle to a torque. Although such torque is fictitious, it could be interpreted as a physical torque such that if it is applied to the mobile robot it will turn.

Let us assume that the human operator establishes the turn angle x_h of the joystick in the following way,

$$\dot{\mathbf{x}}_\mathbf{h}(t) = -\frac{\mathbf{x_h}(t)}{T_h} - \mathbf{y_l}(t) \tag{22}$$

where T_h represents the dynamics of the user's arm and master. From this, a velocity command $\mathbf{u_l} = \left[\begin{smallmatrix}\omega_l \\ v\end{smallmatrix}\right]$ is generated where ω_l is computed as,

$$\omega_l\left(t\right) = k_h \mathbf{x_h}\left(t\right) \tag{23}$$

where $k_h\left[\frac{1}{s}\right]$ converts an angle to an angular velocity command.

Then, the remote system is modeled by (20) and (21) like (1) and (2), and the local system is modeled by (22) and (23) like (3) and (4). Next, we will analyze the absolute transparency of the teleoperation system shown in Fig. 6, where the gains $k_c\left[\frac{rad}{N.m.s}\right]$ and $k_l\left[\frac{1}{s}\right]$ are added.

The remote equivalent system can be represented like (5) and (6) as follows:

$$\begin{bmatrix} \dot{x}\left(t'\right) \\ \dot{y}\left(t'\right) \\ \dot{\theta}\left(t'\right) \end{bmatrix} = \begin{bmatrix} v\cos\theta\left(t'\right) \\ v\sin\theta\left(t'\right) \\ \omega_l(t) - k_l\mathbf{x_h}\left(\theta'\right) - k_c k_f\left(D - \sqrt{x(t')^2 + y(t')^2}\right) \end{bmatrix} \tag{24}$$

$$\mathbf{y_l}\left(t\right) = k_f\left(D - \sqrt{x\left(t''\right)^2 + y\left(t''\right)^2}\right) \tag{25}$$

where $t' = t + \frac{h}{2}$, $\theta' = t$ and $t'' = \theta'' = t - \frac{h}{2}$.

While the local equivalent system can be expressed like (7) and (8) by,

$$\dot{\mathbf{x}}_{\mathbf{h}}\left(t^*\right) = -\frac{1}{T_h}\mathbf{x_h}\left(t^*\right) - \mathbf{y_r}\left(t\right) \tag{26}$$

$$\begin{aligned} \omega_r\left(t\right) = &\left(k_h - k_l\right)\mathbf{x_h}\left(\theta^{**}\right) \\ &- k_c\left(k_f\left(D - \sqrt{x\left(t^{**}\right)^2 + y\left(t^{**}\right)^2}\right)\right) \end{aligned} \tag{27}$$

where $t^* = \theta^* = t + \frac{h}{2}$, and $t^{**} = t$ and $\theta^{**} = t - \frac{h}{2}$.

Comparing (24) and (25) with (20) and (21), and (26) and (27) with (22) and (23) like subsection IV-C, considering $q_l, q_r \leq 1$, the local and remote transparencies can be computed,

$$\begin{aligned} T_L &\leq |k_l| + |Dk_c k_f| \\ T_R &\leq |Dk_c k_f| + |k_l| + |k_h - k_l| \end{aligned} \tag{28}$$

In addition, the instantaneous transparency (12) for this teleoperation system can be deduced as,

$$\begin{aligned} T_t &= |t_{u_a} - t'| + |\theta'' - t| + |t_{y_a} - t^*| + |\theta^{**} - t| + t_m + t_s \\ &= 0 + \frac{h}{2} + \frac{h}{2} + \frac{h}{2} + T_h + 0 = \frac{3}{2}h + T_h \end{aligned} \tag{29}$$

The mobile robot is represented by a kinematic model, then $t_s = 0$ in (29).

Let us suppose that the teleoperation has the following parameters $h = 1s$, $D = 2m$, $k_h = 1\frac{1}{s}$, $T_h = 0.2s$, $k_f = 1N$ and the controller is set to $k_l = 0.5\frac{1}{s}$ and $k_c = 1\frac{rad}{N.m.s}$. Then, these numeric values are used in (28) and (29) to calculate the norm of the absolute transparency (9), considering $k_t = 1$, as follows,

$$\begin{aligned} |\mathbf{T}| &= \sqrt{T_L^2 + T_R^2 + T_t^2} \\ &= \sqrt{(0.5+2\times1\times1)^2 + (2\times1\times1+0.5+0.5)^2 + (1.5\times1+0.2)^2} = 4.259 \end{aligned}$$

The utility of the three components of the absolute transparency is shown in the example, since different values are obtained depending on the human operator, remote system (mobile robot and environment), control scheme (k_l,k_c) and communication channel (h). The achieved result represents the level of absolute transparency of the teleoperation system of a mobile robot with force feedback described by (24), (25), (26) and (27).

Remark: The definition of absolute transparency for teleoperation of mobile robots could be applied in other class of teleoperation system if it can be represented by equations (1) to (8) and if the functions are such that the norms used in equations (10) and (11) are finite.

F. Comparison Between Different Definitions Related to Transparency

Table II shows the advantageous of the definition of absolute transparency respect to the ideal response [34] and the classic transparency in frequency [15], when they are applied to the teleoperation of mobile robots.

V. Design of Control Schemes for Teleoperation of a Mobile Robot

In our delayed teleoperation system, the human operator uses a steering wheel and a joystick to drive the direction and acceleration of a remote mobile robot respectively while he/she receives both visual and force feedback. Here, the user perceives a force feedback only through the joystick.

The human operator generates angular positions $\mathbf{u_l} = \left[\begin{matrix}\phi & \theta\end{matrix}\right]$ driving the joystick and steering wheel, where $0 \leq \phi \leq \frac{\pi}{2}$ and $|\theta| \leq \frac{\pi}{2}$ are the angular positions of them, respectively. These angles are mapped to commands of linear and angular velocity as follows,

$$\mathrm{G}'_{\mathrm{e}}\left(\mathbf{u_l}\right) = \left[\begin{matrix} v_l & \omega_l \end{matrix}\right] = \begin{bmatrix} \mathrm{G}_1 & 0 \\ 0 & \mathrm{G}_2 \end{bmatrix}\left[\begin{matrix} \phi\cos\theta & \phi\sin\theta \end{matrix}\right] \tag{30}$$

where v_l and ω_l are the linear and angular velocity commands, G'_{e} represents the mapping function and $\mathrm{G}_1, \mathrm{G}_2$ convert a position information to a velocity information and are set $\mathrm{G}_1 = \mathrm{G}_2 = 1$ for the sake off simplicity. From the local site, velocity commands $\left[\begin{matrix} v_l & \omega_l \end{matrix}\right]$ are sent to the mobile robot. These commands are modified depending on the control scheme to set the velocity reference $\mathbf{u_r} = \left[\begin{matrix} v_r & \omega_r \end{matrix}\right]$ applied to the mobile robot, where v_r and ω_r are the linear and angular velocity references (see Fig. 7).

The human operator feels the obstacles around the mobile robot through a force f_l which is calculated depending on the tangential component of a force established on the remote

TABLE II
DIFFERENCE RESPECT TO SYSTEM MODEL, TIME DELAY AND QUANTIFICATION.

Definition	System model	Time delay	Quantifiable
Ideal Response	Linear	Constant	Not
Classic Transparency	Linear	Constant	Not
Absolute Transparency	Linear and nonlinear	Constant and variable	Yes

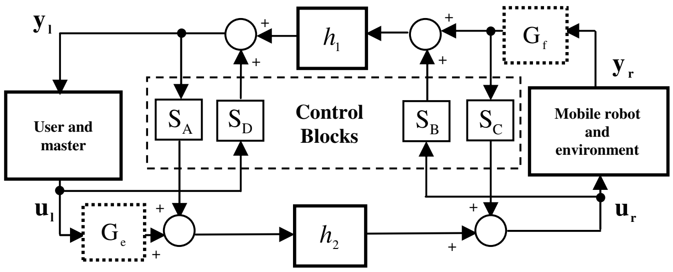

Fig. 7. General control schemes for bilateral teleoperation of mobile robots.

system as $\mathrm{f_{repulsive}} = [\, f_t \quad f_n \,] = (d_{max} - d)\,[\cos\beta \quad \sin\beta\,]$ where d and β describe the distance and orientation between the robot and the obstacles, and d_{max} represents the radio of a repulsion fictitious zone. The force f_l is computed by the used control scheme. In addition, the user visually perceives a position error $\mathbf{e} = [\,\rho \quad \alpha\,]$ of the mobile robot respect to the goal with ρ the distance error and α the angular error. Thus, the signal back-fed to the local site is $\mathbf{y_r} = [\,\mathbf{e}\,(t) \quad f_t\,(t)\,]$, while the perceived feedback by the human operator is $\mathbf{y_l} = [\,\mathbf{e}\,(t-h_1) \quad f_l\,(t)\,]$.

Now, let us assume a general delayed teleoperation system of a mobile robot where the control blocks $\mathrm{S_A}$, $\mathrm{S_B}$, $\mathrm{S_C}$, $\mathrm{S_D}$ described by input-state functions $\mathrm{f_a}$, $\mathrm{f_b}$, $\mathrm{f_c}$, $\mathrm{f_d}$ and state-output functions $\mathrm{g_a}$, $\mathrm{g_b}$, $\mathrm{g_c}$, $\mathrm{g_d}$ respectively as well as the functions for scaling and/or mapping (without dynamics) $\mathrm{G_e}$ and $\mathrm{G_f}$ could be included for the designer, as it is shown in Fig. 7. The states of $\mathrm{S_A}$, $\mathrm{S_B}$, $\mathrm{S_C}$, $\mathrm{S_D}$ are called $\mathbf{x_A}, \mathbf{x_B}, \mathbf{x_C}, \mathbf{x_D}$ respectively.

The teleoperation system shown in Fig. 7 can be described as in (5), (6), (7) and (8) in the following way:

$$\begin{aligned}\dot{\mathbf{x}}_{\mathbf{r}}\,(t+h_2) &= \mathrm{f_r}(\mathbf{x_r}\,(t+h_2)\,, \mathrm{G_e}\,(\mathbf{u_l}\,(t)) + \mathrm{g_a}\,(\mathbf{x_A}\,(t)) \\ &\quad + \mathrm{g_c}\,(\mathbf{x_C}\,(t+h_2))) \\ &= \dot{\mathbf{x}}_{\mathbf{r}}\,(t') = \mathrm{f'_r}\,(\mathbf{x'_r}\,[\theta', t']\,, \mathbf{u_l}\,(t)) \end{aligned} \tag{31}$$

$$\begin{aligned}\mathbf{y_l}\,(t) &= \mathrm{G_f}\,(\mathrm{g_r}\,(\mathbf{x_r}\,(t-h_1))) + \mathrm{g_d}\,(\mathbf{x_D}\,(t)) \\ &\quad + \mathrm{g_b}\,(\mathbf{x_B}\,(t-h_1)) \\ &= \mathrm{g'_r}\,(\mathbf{x'_r}\,[\theta'', t'']) \end{aligned} \tag{32}$$

$$\begin{aligned}\dot{\mathbf{x}}_{\mathbf{h}}\,(t+h_1) &= \mathrm{f_h}(\mathbf{x_h}\,(t+h_1)\,, \mathrm{G_f}\,(\mathbf{y_r}\,(t)) + \mathrm{g_b}\,(\mathbf{x_B}\,(t)) \\ &\quad + \mathrm{g_d}\,(\mathbf{x_D}\,(t+h_1))) \\ &= \dot{\mathbf{x}}_{\mathbf{h}}\,(t^*) = \mathrm{f'_h}\,(\mathbf{x'_h}\,[\theta^*, t^*]\,, \mathbf{y_r}\,(t)) \end{aligned} \tag{33}$$

$$\begin{aligned}\mathbf{u_r}\,(t) &= \mathrm{G_e}\,(\mathrm{g_h}\,(\mathbf{x_h}\,(t-h_2))) + \mathrm{g_a}\,(\mathbf{x_A}\,(t-h_2)) \\ &\quad + \mathrm{g_c}\,(\mathbf{x_c}\,(t)) \\ &= \mathrm{g'_h}\,(\mathbf{x'_h}\,[\theta^{**}, t^{**}]) \end{aligned} \tag{34}$$

where (31) and (32) represent the remote equivalent system whose state is $\mathbf{x_{r_e}} = [\,\mathbf{x_r} \quad \mathbf{x_A} \quad \mathbf{x_B} \quad \mathbf{x_C} \quad \mathbf{x_D}\,]$ and (33) and (34) describe the local equivalent system whose state is $\mathbf{x_{h_e}} = [\,\mathbf{x_h} \quad \mathbf{x_A} \quad \mathbf{x_B} \quad \mathbf{x_C} \quad \mathbf{x_D}\,]$.

In the case of an ideal coupling between the human operator and the environment, the dynamics of the master and robot must be instantaneous ($t_m = 0$ and $t_s = 0$) and the time delay must be null. Due to the dynamics of the master and mobile robot are considered in the definition of absolute transparency, then the local and remote equivalent systems could be compared with a non-delayed teleoperation system described by,

$$\dot{\mathbf{x}}_{\mathbf{r}}\,(t) = \mathrm{f_r}\,(\mathbf{x_r}\,(t)\,, \mathrm{G'_e}\,(\mathbf{u_l}\,(t))) \tag{35}$$

$$\mathbf{y_l}\,(t) = \mathrm{g_r}\,(\mathbf{x_r}\,(t)) \tag{36}$$

$$\dot{\mathbf{x}}_{\mathbf{h}}\,(t) = \mathrm{f_h}\,(\mathbf{x_h}\,(t)\,, \mathbf{y_r}\,(t)) \tag{37}$$

$$\mathbf{u_r}\,(t) = \mathrm{g_h}\,(\mathbf{x_h}\,(t)) \tag{38}$$

where $\mathrm{G'_e}$ is the mapping function used to make the signals of the mobile robot and the master compatible.

Next, the absolute transparency of four control schemes applied to delayed teleoperation of mobile robots with force feedback will be analyzed. We take such control schemes only as examples to show how the absolute transparency can be computed and compared between different control schemes.

A. Teleoperation Without Any Control Scheme

If is not used any control scheme in the teleoperation system, $\mathrm{S_A} = \mathrm{S_B} = \mathrm{S_C} = \mathrm{S_D} = 0$ and $\mathrm{G_e} = \mathrm{G'_e}, \mathrm{G_f} = 1$ (Fig. 7). Considering this in (31), (32), (33) and (34), the delayed teleoperation system can be represented by,

$$\dot{\mathbf{x}}_{\mathbf{r}}\,(t') = \mathrm{f_r}\,(\mathbf{x_r}\,(t')\,, \mathrm{G'_e}\,(\mathbf{u_l}\,(t))) \tag{39}$$

$$\mathbf{y_l}\,(t) = \mathrm{G_f}\,(\mathrm{g_r}\,(\mathbf{x_r}\,(t''))) \tag{40}$$

$$\dot{\mathbf{x}}_{\mathbf{h}}\,(t^*) = \mathrm{f_h}\,(\mathbf{x_h}\,(t^*)\,, \mathrm{G_f}\,(\mathbf{y_r}\,(t))) \tag{41}$$

$$\mathbf{u_r}\,(t) = \mathrm{G'_e}\,(\mathrm{g_h}\,(\mathbf{x_h}\,(t^{**}))) \tag{42}$$

where $t' = \theta' = t + h_2$, $t'' = \theta'' = t - h_1$, $t^* = \theta^* = t + h_1$ and $t^{**} = \theta^{**} = t - h_2$.

Comparing (39), (40), (41) and (42) with (35), (36), (37), and (38) respectively and taking into account the proposed definitions for the instantaneous, the local and the remote transparency; the components of the absolute transparency can be computed as,

$$\begin{aligned} T_t &= (h_1 + h_2) + (h_1 + h_2) + t_m + t_s \\ &\quad + 2\left(\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right)\right) \\ &= 2\,(h_1 + h_2) + t_m + t_s + 2\left(\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right)\right) \end{aligned} \tag{43}$$

$$T_L = 0\ ,\ T_R = 0 \tag{44}$$

For non-delayed direct teleoperation, the absolute transparency is $|\mathbf{T}| = k_t\,(t_m + t_s)$.

B. Gain Applied to the Force Feedback

In this case, $\mathrm{S_A} = \mathrm{S_B} = \mathrm{S_C} = \mathrm{S_D} = 0$, $\mathrm{G_e} = \mathrm{G'_e}$ and $\mathrm{G_f} = 1 + K\,(h_1\,(t) + h_2\,(t))$, where $K > 0$. The delayed teleoperation system can be represented similar to (39), (40), (41) and (42). So, comparing these equations with (35), (36), (37) and (38) considering $q_l, q_r \leq 1$ and $\mathrm{G_f} \neq 1$, the instantaneous transparency (12), the local transparency (10), and the remote transparency (11) can be computed as,

$$\begin{aligned} T_t &= (h_1 + h_2) + (h_1 + h_2) + t_m + t_s \\ &\quad + 2\left(\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right)\right) \\ &= 2\,(h_1 + h_2) + t_m + t_s + 2\left(\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right)\right) \end{aligned} \tag{45}$$

$$T_L \leq |\mathrm{G_f}|\,|\mathrm{g_r}| \leq (1 + K\delta)\,|\mathrm{g_r}| \tag{46}$$

$$T_R \leq |\mathrm{G_f}|\,|\mathrm{f_h}| \leq (1 + K\delta)\,|\mathrm{f_h}| \tag{47}$$

where $\delta = \max\left(h_1(t) + h_2(t)\right)$ for $t \geq 0$.

C. High Degree of Remote Automation

In this case $\mathrm{S_A} = \mathrm{S_B} = \mathrm{S_D} = 0$, and $\mathrm{G_f} = 1$. This scheme is based on combining with the same priority the command generated by the human operator and a signal calculated from a motion controller that includes obstacles avoiding. From (31), (32), (33) and (34), the teleoperation system using the control scheme C can be described by,

$$\dot{\mathbf{x}}_\mathbf{r}(t') = \mathrm{f_r}\left(\mathbf{x_r}(t'), \mathrm{G_e}(\mathbf{u_l}(t)) + \mathrm{g_c}(\mathbf{x_C}(t'))\right) \tag{48}$$

$$\mathbf{y_l}(t) = \mathrm{g_r}\left(\mathbf{x_r}(t'')\right) \tag{49}$$

$$\dot{\mathbf{x}}_\mathbf{h}(t^*) = \mathrm{f_h}\left(\mathbf{x_h}(t^*), \mathbf{y_r}(t)\right) \tag{50}$$

$$\mathbf{u_r}(t) = \mathrm{G_e}\left(\mathrm{g_h}\left(\mathbf{x_h}(t^{**} - h_2)\right)\right) + \mathrm{g_c}\left(\mathbf{x_c}(t^{**})\right) \tag{51}$$

where $t' = \theta' = t + h_2$, $t'' = \theta'' = t - h_1$, $t^* = \theta^* = t + h_1$, $t^{**} = t$ and $\theta^{**} = t - h_2$.

We use a position kinematic controller based on polar coordinates [22]. The obstacles are modeled as repulsive forces where the distance between the robot and the obstacles establish the magnitude of such fictitious or virtual force [35].

This control scheme includes $\mathrm{S_C}$ described by $\mathrm{g_c}(\cdot) = 0.5\mathrm{w}(\cdot) = 0.5\left[\,k_v\tilde{\rho}\cos\tilde{\alpha} \quad k_\omega\tilde{\alpha} + k_v\sin\tilde{\alpha}\cos\tilde{\alpha}\,\right]$, and $\mathrm{G_e} = 0.5\mathrm{G'_e}$. The function $\mathrm{f_c}(\cdot)$ is null since a kinematic controller is used. In $\mathrm{w}(\cdot)$, the parameters k_v and k_ω are the controller gains, and $\tilde{\rho}$ and $\tilde{\alpha}$ represent distance and angular errors defined by,

$$\tilde{\rho} = \rho - k_\rho f_t \ , \ \tilde{\alpha} = \alpha - k_\alpha f_r$$

where ρ and α represent the distance and angular errors of the mobile robot respect to the goal. Fig. 8 shows the variables used in the described controller.

Comparing (48), (49), (50) and (51) with (35), (36), (37), and (38), and taking into account the $q_l, q_r \leq 1$ and the proposed definitions for the instantaneous, the local and the remote transparency; the components of the absolute transparency can be computed as,

$$\begin{aligned} T_t &= (h_1) + (h_1 + h_2) + t_m + t_s + 2\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right) \\ &= 2h_1 + h_2 + t_m + t_s + 2\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right) \end{aligned} \tag{52}$$

$$T_L \leq |\mathrm{f_r}|\left(|\mathrm{f_c}| + |\mathrm{g_c}| + |0.5 - 1|\,|\mathrm{G'_e}|\right) \tag{53}$$

$$T_R \leq 1.5\,|\mathrm{G'_e}|\left(|\mathrm{f_h}| + |\mathrm{g_h}|\right) + 0.5\,|\mathrm{G'_e}|\left(|\mathrm{g_h}| + |\mathrm{f_h}|\right) \tag{54}$$

We remark that a fast autonomous controller (high $|\mathrm{g_c}|$) acting as semi-autonomous part in a teleoperation system has a poor transparency since it forces the robot to a speed higher than the one usually established by the human operator.

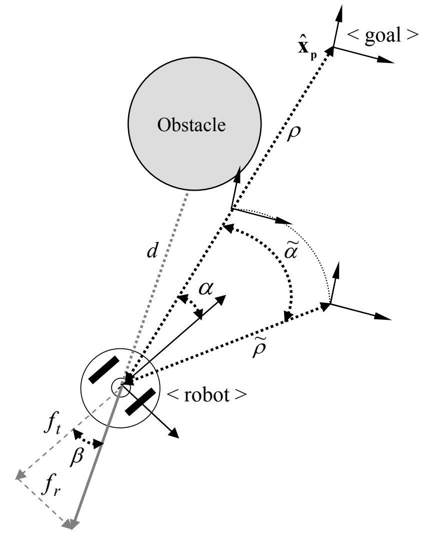

Fig. 8. Repulsive force and distance and angular errors.

D. Controller Based on Remote Transparency

To get a good remote transparency, the remote system should feel that interacts with the human operator. To make this and simultaneously decrease the instantaneous transparency, the control scheme sets $\mathrm{S_B} = \mathrm{S_D} = 0$, $\mathrm{G_e} = \mathrm{G'_e}$, $\mathrm{G_f} = 1$, and $\mathrm{S_A}$ and $\mathrm{S_C}$ are described by $\mathrm{g_a} = -\mathrm{w_h}(\tilde{\rho}_1, \tilde{\alpha}_1)$ and $\mathrm{g_c} = \mathrm{w_h}(\tilde{\rho}_1, \tilde{\alpha}_1)$. The function $\mathrm{w_h}$ has a structure similar to w described in subsection V-C but it uses parameters compatible with the human operator's behavior, as in [22]. The function $\mathrm{w_h}$ includes position and impedance controllers representing the usual reactive behavior of a human operator driving a mobile robot.

On the other hand, the functions $\mathrm{f_a}$ and $\mathrm{f_c}$ are similar to each other and they are represented by a linear system described by,

$$\begin{bmatrix} \dot{\tilde{\rho}}_1 \\ \dot{\tilde{\alpha}}_1 \end{bmatrix} = \begin{bmatrix} \frac{-1}{t_h} & 0 \\ 0 & \frac{-1}{t_h} \end{bmatrix} \begin{bmatrix} \tilde{\rho}_1 \\ \tilde{\alpha}_1 \end{bmatrix} + \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} \tilde{\rho} \\ \tilde{\alpha} \end{bmatrix}$$

where t_h is set to 0.2 seconds. This control scheme is based on [36] and [22], where the command generated by the human operator is changed according to the context felt by him/her and the current context of the remote system. Next, the delayed teleoperation system including the control scheme D can be written by,

$$\begin{aligned} \dot{\mathbf{x}}_\mathbf{r}(t') = \mathrm{f_r}(&\mathbf{x_r}(t'), \mathrm{G'_e}(\mathbf{u_l}(t)) + \mathrm{g_a}(\mathbf{x_A}(t' - h_2)) \\ &+ \mathrm{g_c}(\mathbf{x_C}(t'))) \end{aligned} \tag{55}$$

$$\mathbf{y_l}(t) = G_f\left(g_r\left(\mathbf{x_r}(t'')\right)\right) \tag{56}$$

$$\dot{\mathbf{x}}_\mathbf{h}(t^*) = \mathrm{f_h}\left(\mathbf{x_h}(t^*), \mathbf{y_r}(t)\right) \tag{57}$$

$$\begin{aligned} \mathbf{u_r}(t) = \mathrm{G'_e}&\left(\mathrm{g_h}\left(\mathbf{x_h}(t^{**} - h_2)\right)\right) + \mathrm{g_a}\left(\mathbf{x_A}(t^{**} - h_2)\right) \\ &+ \mathrm{g_c}\left(\mathbf{x_c}(t^{**})\right) \end{aligned} \tag{58}$$

The instantaneous transparency can be deduced like the previous cases as,

$$2h_1 + h_2 + t_m + t_s + 2\mathrm{f_w}\left(\dot{h}_1\right) + \mathrm{f_w}\left(\dot{h}_2\right) \tag{59}$$

where $t'=t+h_2$, $\theta'=t$, $t''=\theta''=t-h_1$, $t^*=\theta^*=t+h_1$, $t^{**}=t$ and $\theta^{**}=t-h_2$.

The remote transparency T_R can be written comparing (57) and (58) with (37) and (38) and considering $q_r \leq 1$, as follows,

$$T_R \leq 2\tilde{\beta} \tag{60}$$

where $\tilde{\beta}$ represents the structural error between the human operator described by $\mathrm{f_h}$ and $\mathrm{g_h}$ and the model $\mathrm{w_h}$.

Now, we analyze how the local transparency can be calculated for this case. Let us assume that $\mathrm{g_a}(\mathbf{x_A}(t)) = -\mathbf{u_l}(t)-\gamma(t)$ and $\mathrm{g_c}(\mathbf{x_c}(t+h_2)) = \mathbf{u_l}(t+h_2)+\gamma(t+h_2)$ with $|\gamma| \leq \bar{\gamma}$. This bound depends on the errors between the human operator and the used model. So, we can re-write (55) as,

$$\dot{\mathbf{x}}_\mathbf{r}(t') = \mathrm{f_r}\left(\mathbf{x_r}(t'), \mathrm{G_e}\left(-\gamma(t'-h_2)+\gamma(t')+\mathbf{u_l}(t')\right)\right) \tag{61}$$

where $t'=t+h_2$ and $\theta'=t$.

The local transparency can be computed, comparing (61) and (56) with (35) and (36) and considering $q_l \leq 1$, as follows,

$$T_L \leq 2\left|\mathbf{f_r}\right|\bar{\gamma} \tag{62}$$

In this control scheme, the local and remote transparencies are better if the model errors are smaller.

E. Theoretical Comparison Between Control Schemes

To get a quantitative result of the level of absolute transparency, the models (structure and parameters) of the teleoperation system must be known. When the models are not available, the proposal allows, at least, comparing different control schemes by analyzing their relative advantages and disadvantages. The teleoperation without control scheme has a better absolute transparency than the control scheme B, since in last scheme the force feedback is modified, changing the perception of the user about the obstacles, as it is shown in (44), (46) and (47). Comparing (43) with (52), the control scheme C has an instantaneous transparency better than A, but the absolute transparency $\mathbf{T}$ of C could be worse, since generally it prioritizes stability with fast convergence using for this a structural change that causes loss in the remote (53) and local (54) transparencies. Finally, comparing (59), (60) and (62) with the components of the absolute transparency of the other schemes, the control scheme D can have a better if an acceptable model of the human operator's behavior is used. Table III summarizes the comparison of the control schemes A, B, C and D respect to local, remote and instantaneous transparency, where each item is classified as "very good", "good", "fair" and "bad".

TABLE III
COMPARISON BETWEEN DIFFERENT CONTROL SCHEMES.

Scheme	Local transparency	Remote transparency	Instantaneous transparency
A	Very Good	Very Good	Bad
B	Fair	Fair	Bad
C	Fair	Bad	Fair
D	Good	Good	Fair

VI. Analysis from Experiments of Teleoperation of Mobile Robots

In this section, experiments of bilateral teleoperation of a mobile robot are shown, where the control schemes A, B, C, and D described in last section are tested for different time delays.

In these experiments, four human operators drive a mobile robot to a pre-established goal avoiding and feeling the closeness of an obstacle (placed on the remote environment) through a virtual force. A requirement made to each user is that he goes straight at maximum linear velocity $\left(0.4\left[\frac{m}{s}\right]\right)$ until a significant force be felt in his hand. From this moment, he will change his command (turn, decrease the linear velocity, etc.) as he want. Generally, the force feedback is used in teleoperation of mobile robots when other sensory modalities are blocked or unreliable (for example driving with poor visibility area) or the operation itself is extensively mechanical. In these cases, the human operator haptically perceives the motion state and/or an external force (real or virtual).

On the other hand, the master used in this work is composed by a Genius steering wheel and a joystick manufactured by the INAUT, University of San Juan. The slave is a Pioneer 3DX mobile robot made by *Activmedia*, Fig. 9. Such robot has two internal PID controllers to drive the two electrical motors depending on the velocity reference ($\mathbf{u_r}$ in Fig. 7). The angular positions of the joystick and steering wheel are measured from potentiometer-type sensors, while the fictitious force and the position of the mobile robot are obtained from a laser sensor, and encoders on board it. The human operator and mobile robot are linked via an intranet network adding FIFO buffers to increase the time delay.

Table IV shows the results obtained in the teleoperation experiments, where the mean values $e_v\left[\frac{m}{s}\right]$, $e_\omega\left[\frac{rad}{s}\right]$ and $e_f\left[N\right]$ respect to all experiments (192 = number of schemes x number of operators x number of delays x quantity of experiments for each item) are calculated taking into account the mean squared error between $v_l(t-h_2)$ and $v_r(t)$, the mean squared error between $\omega_l(t-h_2)$ and $\omega_r(t)$ and the mean squared error between $f_t(t-h_2)$ and $f_l(t)$, respectively. In addition, P_c is the estimated collision percentage calculated as the number of collisions divided by the number of experiments, and t_e is the

Fig. 9. Mobile robot teleoperated through a joystick with force feedback and steering wheel.

TABLE IV
EXPERIMENTS OF TELEOPERATION OF A MOBILE ROBOT WITH FORCE FEEDBACK.

Scheme	Delay-type	$\mathbf{e_v}$	$\mathbf{e}_\omega$	$\mathbf{e_f}$	$\mathbf{P_c}$	$\mathbf{t_e}\,[s]$
A	1	0	0	0	0	17
A	2	0	0	0	0	18.2
A	3	0	0	0	0.4	26
A	4	0	0	0	1	X
B	1	0	0	0	0	17
B	2	0	0	0	0	18.2
B	3	0	0	0.62	0.3	21.1
B	4	0	0	0.89	0.4	32
C	1	0.25	0.28	0	0	14.9
C	2	0.22	0.3	0	0	17.9
C	3	0.14	0.36	0	0	18.5
C	4	0.17	0.43	0	0	18.8
D	1	0	0	0	0	17
D	2	0.04	0.01	0	0	19.1
D	3	0.1	0.03	0	0	20.7
D	4	0.11	0.05	0	0	23.2

mean value of the time interval to reach the goal (X indicates a collision, in that case the experiment was stopped).

If the magnitude and variation rate of the time delay is greater, then the absolute transparency is worse independently from the control scheme used.

The delay-types used in the experiments, whose results are shown in Table IV, are the following:

1) Without delay.
2) Symmetric constant delay where $h_1 = h_2 = 0.5$ seconds.
3) Asymmetric time-varying delay where the delays h_1 and h_2 are sawtooth periodic signals with slopes ± 0.1 and ± 0.2 and magnitude bounded by 0.75 and 1.5 seconds, respectively. The initial time instant is random.
4) Symmetric time-varying delay where the delays h_1 and h_2 are sawtooth periodic signals with slopes ± 0.2 and magnitude bounded by 1.5 seconds. The initial time instant is random.

Fig. 10, 11, 12 and 13 show the trajectories followed by the mobile robot teleoperated by the same human operator for different time delays using the control schemes A, B, C and D, respectively; where the non-delayed teleoperation with a controller A is taken as pattern since this case has an ideal transparency.

The scheme D has an absolute transparency better than the other ones (subsection V-E). This can be appreciated in Table IV and figures 10 to 13, where the scheme D has low values of e_v, e_ω, e_f and a good similarity with the non-delayed teleoperation (using scheme A) respect to the curve made by the mobile robot. However, all schemes lose transparency if the time delay is bigger (in magnitude and variation rate), which is reflected in the trajectories followed by the mobile robot and the time to complete the task (loss of instantaneity).

Although there is not a direct relation between the remote

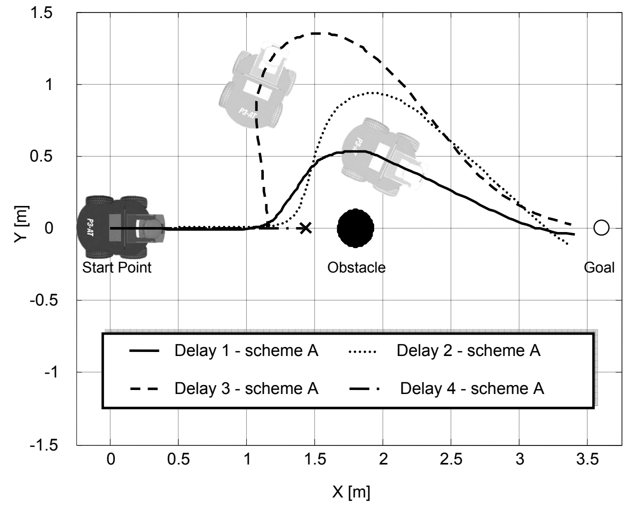

Fig. 10. Trajectories followed by the remote mobile robot using the scheme A.

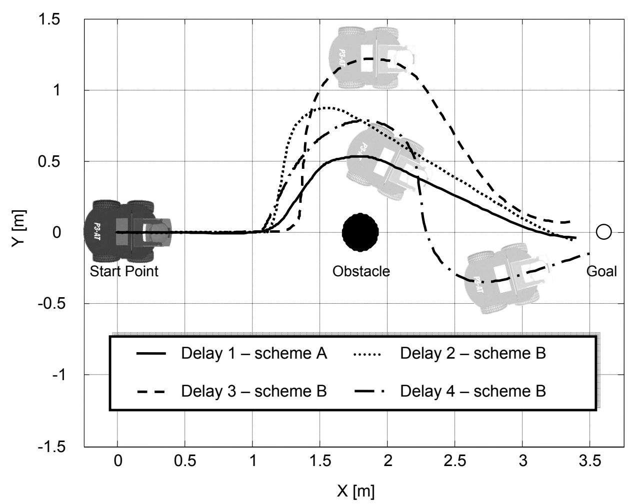

Fig. 11. Trajectories followed by the remote mobile robot using the scheme B.

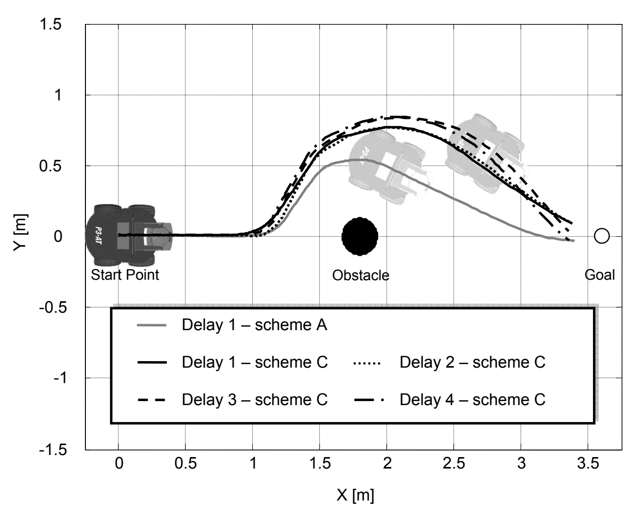

Fig. 12. Trajectories followed by the remote mobile robot using the scheme C.

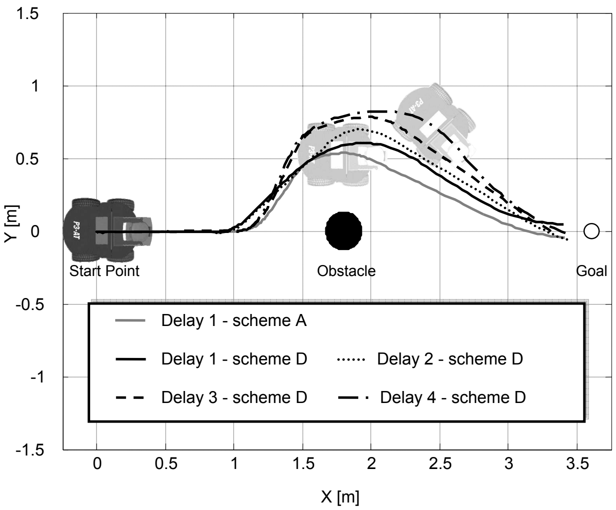

Fig. 13. Trajectories followed by the mobile robot using the scheme D.

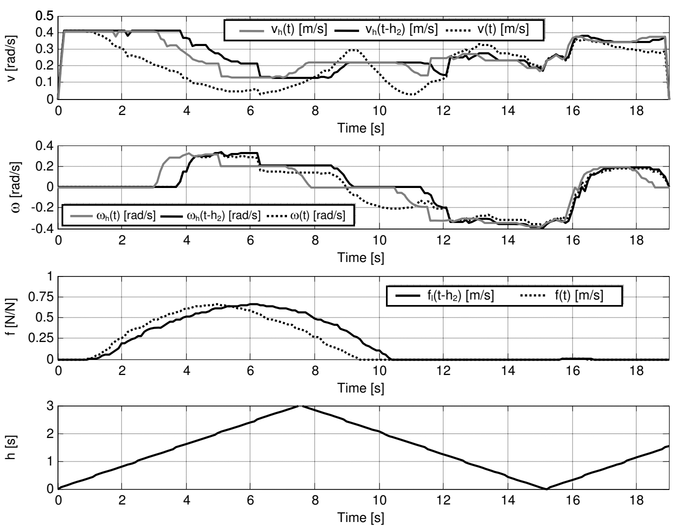

Fig. 14. Linear and angular velocity commands and real velocities for a delay-type 4 using scheme D.

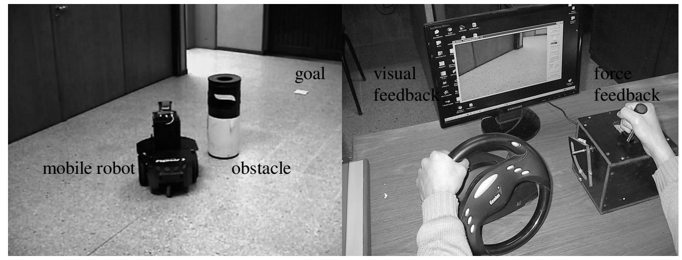

Fig. 15. Image of the teleoperation experiment carried out.

and local transparencies and the values of e_v, e_ω and e_f (e.g. these values are not independent of the delay); they show that the local and remote transparency are worse when the command and feedback signals are changed.

Fig. 14 shows how the commands of linear and angular velocity generated by the human operator arrive to the remote site and their differences respect to the control signals applied by the control scheme D in the case of a delay-type 4. In addition, the force calculated in the remote site and the force applied to the master (felt by the human operator) are shown in this figure. In these experiments, the force feedback provides an extended physiological proprioception (EPP) to the human user while he drives the mobile robot in order to achieve the position goal.

Fig. 15 shows a photo of this experiment in about 6 seconds (see Fig. 14). This figure shows simultaneously the mobile robot (on the left) teleoperated by the human operator through an interface (on the right). The human operator drives the mobile robot using his hands to maneuver the steering wheel and joystick. Last figure shows a typical case where the human operator does not watch the obstacle although the mobile robot is near it but he perceives the closeness of such obstacle through a force feedback in his hand.

VII. Conclusion

In this paper, a new definition called absolute transparency has been proposed for its use in systems of bilateral teleoperation of mobile robots.

The definition is bilateral intrinsically and is represented by a 3D vector, whose norm allows comparing different teleoperation systems. The components of the absolute transparency vector are called local transparency, remote transparency and instantaneous transparency. The local transparency gives as a result the measure of how the human operator feels the remote system, while the remote transparency allows quantifying how the remote system feels the human operator. These two components are independent of the magnitude of the time delay and depend on the used control scheme. The instantaneous transparency quantifies the master dynamics, the slave dynamics, the loss of instantaneity, the apparent delay felt by the human operator and the remote system and the effects of the distortion and information loss produced by a time varying delay which can be symmetric or asymmetric. This component depends on the used control scheme and the magnitude and variation rate of the time delay.

A theoretical analysis of absolute transparency of four control schemes was carried out and tested from experiments teleoperating a mobile robot with force feedback. A teleoperation system works better in practice respect to other ones if it has a better absolute transparency. This conclusion is valid if the compared schemes have similar conditions respect to the quantity and quality of visual information.

Some typical questions in teleoperation systems of mobile robots can be addressed using absolute transparency, such as the fact that autonomous controllers with a high speed response (high gains) might not have an adequate performance acting as semi-automatic controllers in a teleoperation system. Having a measure of absolute transparency which is quantitative and separated in different components will allow searching the best trade-off between stability and transparency for a given application, using one more tool.

In general, the designer will try to decrease the absolute transparency (involving all components), but the importance of each component will depend on the control-type and task. For example, if a supervisory control is used then the human operator should "see" the remote system the best possible (good local transparency) while the remote transparency not necessarily should be good since the remote system should "see" a good autonomous controller instead of the human operator. However, the absolute importance between the local and remote transparencies respect to the instantaneous transparency is an open research, since k_t in (9) can not be set arbitrarily and it should be estimated. Intuitively, the component in time should have a high relevance due to testing a delayed teleoperation system without any control scheme (null local and remote transparencies) would seem that quickly degrades its absolute transparency as the time delay is bigger.

The concept of absolute transparency has sense in stable or passive teleoperation systems. So, the absolute transparency could be used to complement the stability concept and thus, both could be analyzed together by the designers as criterion to design control schemes applied to systems of bilateral teleoperation of mobile robots.

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