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Teleoperation of a mobile robot with time-varying delay and force feedback

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SUMMARY

This paper proposes a prediction system and a command fusion to help the human operator in a teleoperation system of a mobile robot with time-varying delay and force feedback. The command fusion is used to join a remote controller and the delayed user's commands. Besides, a predictor is proposed since the future trajectory of the mobile robot is not known *a priori* being it decided online by the user. The command fusion and predictor are designed based on the time delay and the current context measured through the crash probability. Finally, the proposed scheme is tested from teleoperation experiments considering time-varying delay as well as force feedback.

KEYWORDS: Force feedback; Mobile robots; Teleoperation; Time-varying delay.

Nomenclatures

$\mathbf{x_r} = [\,x_r\ y_r\ \theta_r\,]$: position and orientation of the mobile robot

ρ, α: distance and angular errors between the robot and goal

$\mathbf{f_e} = [\,f_t\ f_r\,]$: fictitious force

$\tilde{\rho}, \tilde{\alpha}$: distance and angular errors between the mobile robot and the goal modified by the fictitious force

r: distance between robot and obstacle

h_2: forward delay

h_1: backward delay

h: round-trip delay

v, ω: linear and angular velocity of the mobile robot

P_c: collision probability

$\mathbf{x_h} = \mathbf{x}(t-h)$

$\tilde{\rho}_h = \tilde{\rho}(t-h), \tilde{\alpha}_h = \tilde{\alpha}(t-h)$

$\mathbf{u_l}(t-h) = [\,v_h(t-h)\ \omega_h(t-h)\,]$: human operator's command on the remote site

$\hat{\mathbf{x}}_\mathbf{p} = \left[\,\hat{x}_p\ \hat{y}_p\ \hat{\theta}_p\,\right]^{\mathrm{T}}$: prediction of the goal

$\mathbf{x}$: state vector with Euclidean norm $|\mathbf{x}|$

$\mathbf{x}^{\mathrm{T}}$: transposed vector of $\mathbf{x}$

f, g, f_1, f_2: nonlinear functions

$|g|$: induced norm of the function $g\,(\cdot)$

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1. Introduction

Robot teleoperation allows human operators to make different tasks in remote or hazardous environments. One of the most attractive areas is the teleoperation of mobile robots since the remote workspace is unlimited. In these systems, the human operator drives a mobile robot moving in a remote environment. Today, there are many applications for robot teleoperation, including telemedicine, exploration, entertainment, tele-manufacturing, rescue, UAV teleoperation, and many more.[6,26,31] However, it is known that the presence of time delay may induce instability or poor performance in a delayed control system.[16,19,21,30] From this, numerous control schemes have been proposed for the standard teleoperation between master–slave manipulators[3,9] with force feedback,[28] such as delay compensation based on transmission of wave variables,[2,17,33] tele-programming[7,8] and supervisory control,[5,20] predictive display,[4,11] control based on transparency,[13] remote impedance control,[12,18] passivity-based control considering the discrete system,[24] and many more such as refs. [25, 32, 35] among others.

On the other hand, although various strategies used in teleoperation of manipulators could be used in teleoperation of mobile robots, generally the design and the performance analysis are different[34] and the application of force feedback is commonly associated to a virtual force.[29,36] Some papers present in the current literature about teleoperation of mobile robots that show a stability analysis and experiments with time delay are the following ones: event-based control,[6] where the transmission of commands and force feedback is discontinuous, while the bandwidth of the force perceived by the user is limited by the magnitude of the time delay; control based on passivity[14] where only constant delay is considered,[23] where the delayed command generated by the human operator is compensated by using a model of human's reaction, but only visual feedback is used and the goal is known, and ref. [27] where augmented reality is used. The papers mentioned above represent quite well the control schemes applied to these systems. 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 researching area.

This paper proposes a control scheme applied to teleoperation of a mobile robot with force feedback and time-varying delay. While the user receives delayed force

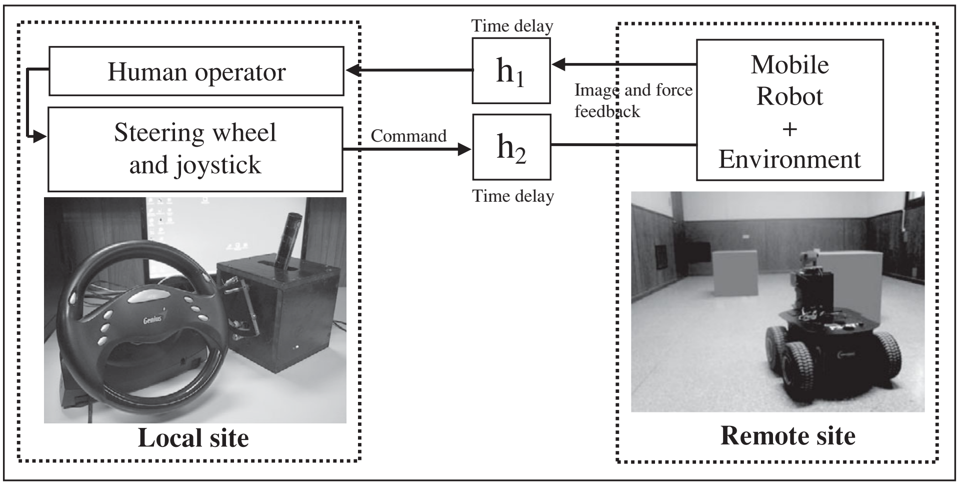

Fig. 1. General block diagram of a teleoperation system of a mobile robot.

and generates delayed commands permanently, the scheme predicts the user's intention and fuses such commands with a stable controller in order to achieve a collision-free trajectory of the mobile robot. The joining between the user's command and the output of the controller depends on the current magnitude of the time-varying delay and the collision probability measured online. Instead, the force sent to the user is not changed by the proposed scheme so as not to distort the user's perception about the remote environment. On the other hand, the motion controller receives the reference from a prediction system, which is used since the goal is unknown. Such prediction is based on the delayed command generated by the human operator but compensated by using the difference between the current crash probability and the one felt by the user at the moment of sending his command. In addition, the remote controller uses a nonlinear position control and an impedance control and was selected since it is compatible with the normal driving of a human operator.[23] Finally, the performance of the designed control scheme in front of possible collisions with obstacles is tested from teleoperation experiments of a mobile robot in presence of time-varying delays.

The paper is organized as follows: section 2 presents the statement of the control problem. In Section 3, a control scheme for teleoperation of mobile robots is proposed. The stability of the delayed teleoperation system is analyzed in Section 4. A function to join the control signals provided by the human operator and a remote controller is proposed in Section 5. In Section 6, the performance of the proposed control scheme is analyzed making use of teleoperation experiments. Finally, the conclusions of this paper are given in Section 7.

2. Statement of the Control Problem

This section describes the control problem analyzed for a delayed teleoperation system of a mobile robot. The human operator drives a mobile robot using a steering wheel and a joystick to generate velocity commands, which are sent by a communication channel to the mobile robot placed on a remote site. Simultaneously, the user receives visual and force feedback, as it is shown in Fig. 1.

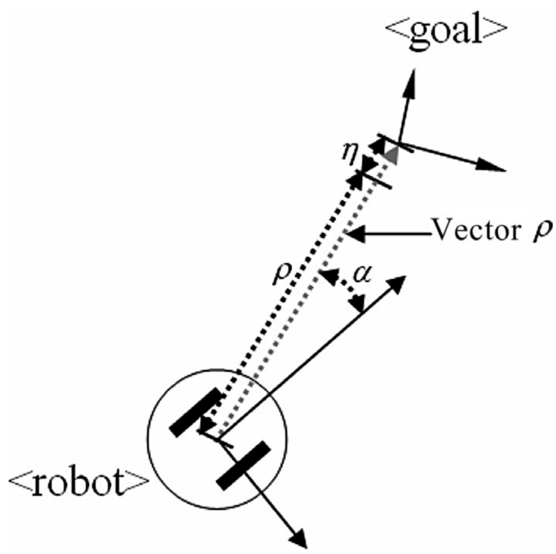

Fig. 2. State of a mobile robot described in polar coordinates.

Let us consider the mobile robot located at a nonzero distance from the reference frame called <goal>. In addition, attached to the robot, there exists the frame called <robot>. The vehicle position is described in polar coordinates, where the state variables that define the mobile robot position are the distance error ρ and the angular error α (the final orientation is not considered). They are measured between the frame *<goal>* and the frame *<robot>* (Fig. 2).

The kinematic equations, considering a time-varying reference (goal), can be written for the distance error and the angular error as in ref. [1]

$$\begin{cases} \dot{\rho} = -v\cos\alpha + \dot{S}_\rho, \\ \dot{\alpha} = -\omega + v\dfrac{\sin\alpha}{\rho+\eta} - \dfrac{\dot{S}_\alpha}{\rho+\eta}, \end{cases} \tag{1}$$

where v and ω are the linear and angular velocity of the mobile robot, respectively; $\rho + \eta$ is the real distance error between the goal and the mobile robot, where η is a positive constant value; $\dot{S}_\rho$ is the derivative of the goal on the direction of the vector ρ; and $\dot{S}_\alpha$ is the derivative of the goal on the

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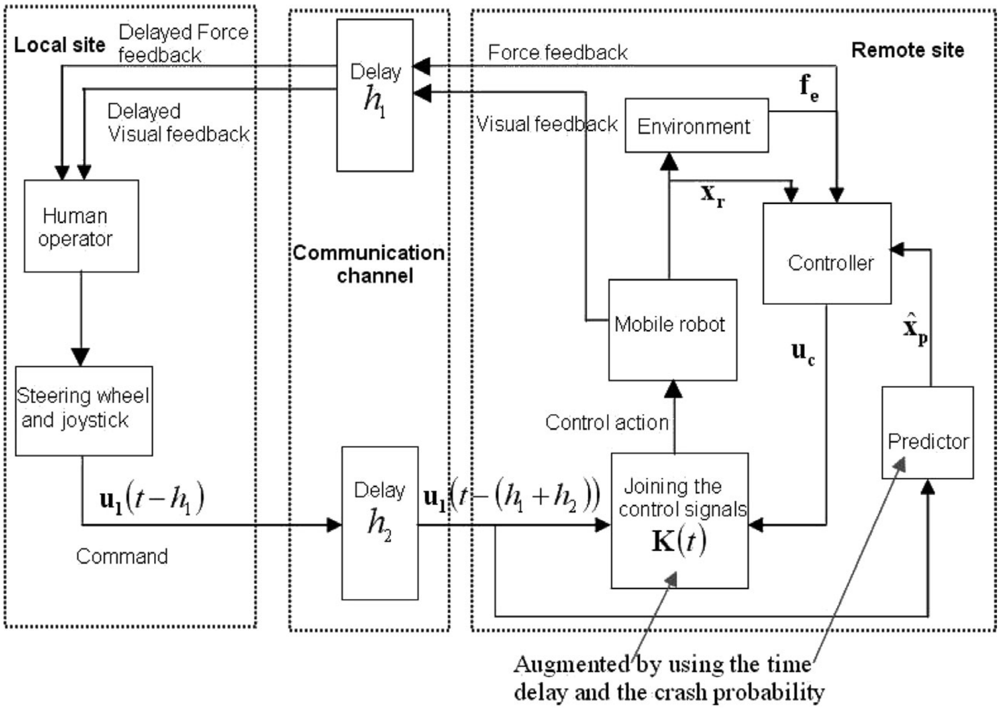

Fig. 3. Proposed control scheme for teleoperation of a mobile robot.

direction perpendicular to the vector ρ. The controller will use ρ instead of $\rho + \eta$ to avoid the singularity in the system at cost of losing precision in the position control.

On the other hand, the communication channel is represented by a time-varying delay h defined as

$$h(t) = h_1(t) + h_2(t) \leq h_m, \tag{2}$$

where h_2 is the forward delay (from the local site to the remote site) and h_1 is the backward delay (from the remote site to the local site), as it is shown in Fig. 1.

The objective is to design a control scheme to set the control actions v and ω helping the human operator drive a mobile robot through a teleoperation system with time-varying delay.

3. Control Scheme for Delayed Teleoperation of a Mobile Robot

A control scheme is proposed for the teleoperation of a mobile robot with time-varying delay, where a predictor and commands fusion are enhanced by using the magnitude of the time delay and the crash probability. The control scheme links the human operator and a remote controller. Figure 3 shows a block diagram of the delayed teleoperation system adding the proposed scheme. The user permanently sees and feels the delayed visual and force feedback sent from the mobile robot that navigates by an environment with obstacles. The predictor computes the position reference of the remote controller since the global goal is not known *a priori*. Such controller is formed by both a position controller and an impedance controller in order to avoid possible collisions of the robot. Finally, the command generated by the user is fused with the command computed by the controller by using a proposed function. On the other hand, the user feels the closeness of the obstacles by means of force feedback, which improves his perception of the environment. 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).

The control scheme proposes calculating the control action applied to the mobile robot joining on the remote site the delayed command $\mathbf{u_l}(t - (h_1 + h_2))$ provided by the human operator and the control signal $\mathbf{u_c}(t)$ computed by a remote controller (see Fig. 3) by using a function $\mathbf{K}(t)$ as follows:

$$\begin{aligned}\begin{bmatrix} v \\ \omega \end{bmatrix} &= (\mathbf{I} - \mathbf{K}(t))\,\mathbf{u_l}(t-h) + \mathbf{K}(t)\,\mathbf{u_c}(t) \\ &= (\mathbf{I} - \mathbf{K}(t))\begin{bmatrix} v_l(t-h) \\ \omega_l(t-h) \end{bmatrix} + \mathbf{K}(t)\begin{bmatrix} v_c \\ \omega_c \end{bmatrix},\end{aligned} \tag{3}$$

where $\mathbf{I} = [\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}]$, $\mathbf{K} = [\begin{smallmatrix} K(t) & 0 \\ 0 & K(t) \end{smallmatrix}]$ with $0 \leq K(t) \leq 1$ for all t and $-\dot{K} < \beta$ with $\beta > 0$, $v_l(t-h)$ and $\omega_l(t-h)$ are the linear and angular velocity commands received in the remote site from the human operator, respectively, v_c and ω_c are the linear and angular velocity commands computed by the remote controller, respectively, and v and ω are the control actions applied to the mobile robot (1).

Note: $\mathbf{u_l}(t)$ represents the command generated by the human operator when $h_1 = h_2 = 0$.

3.1. Prediction augmented by using the crash probability

The proposed prediction module generates a prediction where the human operator wants the mobile robot to go.

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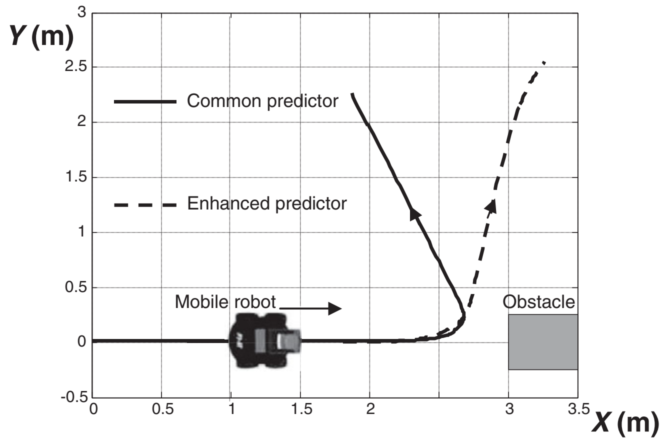

Fig. 4. Enhanced predictor working for $h_1 = h_2 = 1.5$ s.

The prediction is bounded independently of the magnitude of the time delay. The algorithm predicts a position reference based on the commands generated by him but such reference is compensated by using the current crash probability $P_c(t)$ and the one felt by him $P_c(t-h)$ at the moment of sending his command. This prediction called $\hat{\mathbf{x}}_\mathbf{p} = [\hat{x}_p\ \hat{y}_p\ \hat{\theta}_p]^\mathrm{T}$ is computed on the remote site as follows:

$$\begin{aligned}\hat{\theta}_p(t) &= \theta_r(t) + G_\omega[\omega_l(t-h)]\Delta P_c,\\ x_p(t) &= x_r(t) + G_v[v_l(t-h)\cos\hat{\theta}_p(t)],\\ \hat{y}_p(t) &= y_r(t) + G_v[v_l(t-h)\sin\hat{\theta}_p(t)],\end{aligned}\tag{4}$$

where $\Delta P_c = 1 - (P_c(t-h) - P_c(t))$ if $P_c(t) < P_c(t-h)$ and $\Delta P_c = 1$ otherwise. In addition, $\mathbf{u_l}(t-h) = [v_l(t-h)\ \omega_l(t-h)]^\mathrm{T}$ is the user's command with time delay, $\mathbf{x_r} = [x_r\ y_r\ \theta_r]^\mathrm{T}$ is the position and orientation of the mobile robot in Cartesian coordinates, h is the current time delay, and h_0 is a parameter that increases the prediction horizon, which is necessary when h is zero, and $G_v = k_1 \tanh(\frac{h+h_0}{k_1})$ and $G_\omega = k_2 \tanh(\frac{h+h_0}{k_2})$ allow assuring that the estimated position $\hat{\mathbf{x}}_\mathbf{p}$ is bounded, where $k_1, k_2 > 0$.

Let us assume that $\dot{v}_h$ and $\dot{\omega}_h$ are bounded, then from Eq. (4), $\dot{\hat{\mathbf{x}}}_\mathbf{p}$ is bounded too. Projecting $\dot{\hat{\mathbf{x}}}_\mathbf{p}$ on the vector ρ and on its perpendicular direction, $\dot{S}_\rho$ and $\dot{S}_\alpha$ can be established, respectively, to be used in Eq. (1).

Figure 4 shows a comparison between the use of a common predictor ($\Delta P_c = 1$ in Eq. (4)) and an enhanced predictor (variable ΔP_c) for a typical situation in a delayed teleoperation, where the user avoids an obstacle and continues moving the robot forward. The goal and the remote environment are not known; therefore, the use of a predictor is necessary. In this example, the predictor output is directly applied to a remote controller. The enhanced predictor avoids the backward motion caused by an inadequate prediction made by a common predictor, which only uses the information of the mobile robot and the delayed user's command, while the enhanced predictor also uses the mismatch between the crash probability "felt" by the user and the one currently measured on the remote site.

3.2. Free-collision controller

To avoid collisions between the mobile robot and the obstacles and reach a position reference, a nonlinear position controller and an impedance controller are used on board of the mobile robot. Figure 5 shows the used controller that takes the signal $\hat{\mathbf{x}}_\mathbf{p}$ computed by the predictor (Section 3.1) as its reference.

3.2.1. Impedance controller. An impedance controller based on a fictitious force defined from the distance between the robot and the obstacles is used. The magnitude of the repulsive fictitious force f is calculated as

$$f(t) = k_3 - k_4 r(t),\tag{5}$$

where k_3, k_4 are positive constants such that $k_3 - k_4 r_{\max} = 0$ and $k_4 - k_3 r_{\min} = 1$, $r_{\max}$ is the robot-obstacle maximum distance, $r_{\min}$ is the robot-obstacle minimum distance, and r is the robot-obstacle distance ($r_{\min} \le r(t) \le r_{\max}$). On the other hand, the angle of the fictitious force ϕ depends on the orientation of the obstacle with respect to the mobile robot (Fig. 6).

The tangential fictitious force and the normal fictitious force are calculated as $f_t = f\cos\phi$ and $f_r = f\sin\phi$, respectively. The tangential force is back-fed to the user through a joystick with force-reflection. The force value back-fed to the user is not modified by the control scheme in order to keep his perception of the obstacles.

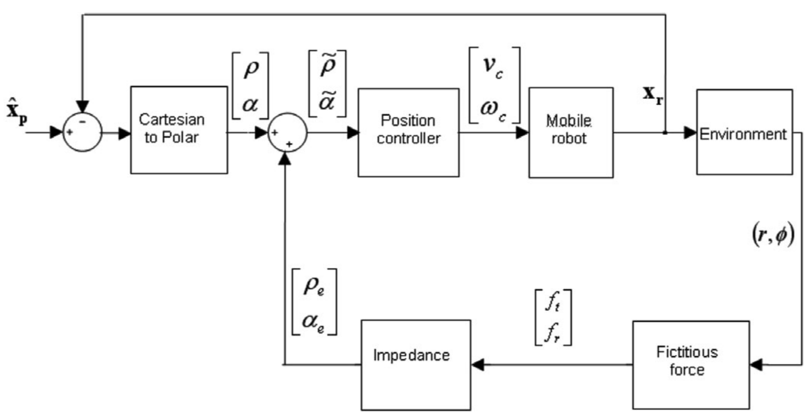

Fig. 5. Motion controller.

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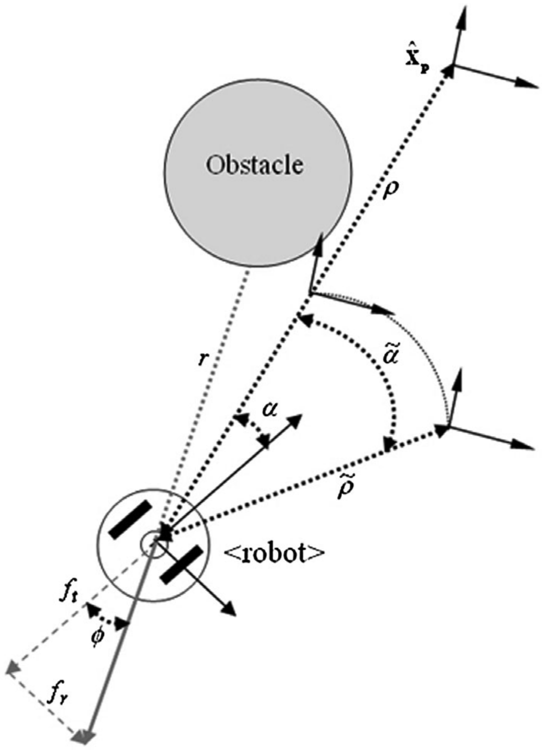

Fig. 6. Relation between the repulsive force and the distance and angular errors.

The impedance model is defined as

$$[\,\rho_e \quad \alpha_e\,]^{\mathrm{T}} = \mathbf{Z}\mathbf{f_e}, \tag{6}$$

where $\mathbf{f_e} = [\,f_t \;\; f_r\,]^{\mathrm{T}}$, $\mathbf{Z} = [\begin{smallmatrix} K_\rho & 0 \\ 0 & K_\alpha \end{smallmatrix}]$ with $K_\rho, K_\alpha > 0$ describing the elasticity parameters, f_t is the fictitious force along the robot motion direction, and f_r is the fictitious force normal to f_t.

When the mobile robot navigates interacting with an environment, the state is defined as (see Fig. 6)

$$[\,\tilde{\rho} \quad \tilde{\alpha}\,]^{\mathrm{T}} = [\,\rho \quad \alpha\,]^{\mathrm{T}} - [\,\rho_e \quad \alpha_e\,]^{\mathrm{T}}, \quad \text{with} \quad \tilde{\rho} \geq 0 \oplus, \tag{7}$$

where ρ, α are error signals respect to a time-varying position reference.

3.2.2. Nonlinear position controller. The controller uses a nonlinear position controller to achieve a position reference. The controller is represented by

$$\mathbf{u_c} = \begin{bmatrix} v_c \\ \omega_c \end{bmatrix} = \begin{bmatrix} k_e \tilde{\rho} \cos\tilde{\alpha} \\ k_q \tilde{\alpha} + k_e \sin\tilde{\alpha}\cos\tilde{\alpha} \end{bmatrix}, \tag{8}$$

where $k_e, k_q > 0$ are the controller parameters, and $\tilde{\rho}$ and $\tilde{\alpha}$ are the distance and angular errors, both are computed as in Eq. (7), where ρ and α are calculated from the comparison between the position and orientation of the mobile robot $\mathbf{x_r} = [\,x_r \quad y_r \quad \theta_r\,]^{\mathrm{T}}$ and the prediction $\hat{\mathbf{x}}_\mathbf{p} = [\,\hat{x}_p \quad \hat{y}_p \quad \hat{\theta}_p\,]^{\mathrm{T}}$. The output of the controller is $\mathbf{u_c}$ that includes components of linear v_c and angular ω_c velocity.

In ref. [23], the model (8) was used to describe the behavior of a human operator driving a mobile robot. We describe the control signal provided by the human operator as

$$\begin{aligned} \mathbf{u_l}(t-(h_1+h_2)) &= \begin{bmatrix} v_l\,(t-h) \\ \omega_l\,(t-h) \end{bmatrix} \\ &= \begin{bmatrix} k_v \tilde{\rho}_h \cos\tilde{\alpha}_h \\ k_\omega \tilde{\alpha}_h + k_v \sin\tilde{\alpha}_h \cos\tilde{\alpha}_h \end{bmatrix}, \end{aligned} \tag{9}$$

where $\tilde{\rho}_h = \tilde{\rho}(t-h), \tilde{\alpha}_h = \tilde{\alpha}(t-h)$, and the parameters $k_v, k_\omega > 0$ are different for each human operator.[23]

4. Stability Analysis of the Delayed Teleoperation System

From the kinematic equations of a mobile robot considering a time-varying goal (1), the evolution of the state of the teleoperation system $[\,\tilde{\rho}\;\tilde{\alpha}\,]^{\mathrm{T}}$ defined in Eq. (7) can be described by

$$\begin{cases} \dot{\tilde{\rho}} = -v\cos\tilde{\alpha} + \dot{S}_\rho - K_\rho \dot{f}_t, \\ \dot{\tilde{\alpha}} = -\omega + v\dfrac{\sin\tilde{\alpha}}{\tilde{\rho}+\eta} - \dfrac{\dot{S}_\alpha - K_\alpha \dot{f}_r}{\tilde{\rho}+\eta}. \end{cases} \tag{10}$$

From now on, $\mathbf{x} = \mathbf{x}(t)$ and $\mathbf{x_h} = \mathbf{x}(t-h)$ will be used to describe the state and the delayed state of the teleoperation system. The system (10) can be represented as

$$\dot{\mathbf{x}} = f_1\,(\mathbf{x}, \mathbf{u}) + \mathbf{p_1}, \tag{11}$$

where the state of the teleoperation system is given by $\mathbf{x} = [\,\tilde{\rho}\;\tilde{\alpha}\,]^{\mathrm{T}}$ with

$$\begin{bmatrix} \dot{\tilde{\rho}} \\ \dot{\tilde{\alpha}} \end{bmatrix} = f_1\left(\begin{bmatrix} \tilde{\rho} \\ \tilde{\alpha} \end{bmatrix}, \begin{bmatrix} v \\ \omega \end{bmatrix}\right) = \begin{bmatrix} -v\cos\tilde{\alpha} \\ -\omega + v\dfrac{\sin\tilde{\alpha}}{\tilde{\rho}+\eta} \end{bmatrix}, \tag{12}$$

and

$$\mathbf{p_1} = \begin{bmatrix} \dot{S}_\rho - K_\rho \dot{f}_t \\ \dfrac{-(\dot{S}_\alpha - K_\alpha \dot{f}_r)}{\tilde{\rho}+\eta} \end{bmatrix} \leq \begin{bmatrix} \dot{S}_\rho - K_\rho \dot{f}_t \\ \dfrac{-(\dot{S}_\alpha - K_\alpha \dot{f}_r)}{\eta} \end{bmatrix} \tag{13}$$

represents a perturbation depending on the derivative of the fictitious force and the derivative of the goal. Let us assume that $\dot{S}_\rho, \dot{S}_\alpha, \dot{f}_t, \dot{f}_r$ are bounded, then $|\mathbf{p_1}|$ is bounded too.

Applying the control action (3) that joins Eqs. (8) and (9) to the mobile robot (10), the closed-loop teleoperation system can be represented by

$$\begin{aligned} \dot{\tilde{\rho}} &= -[K k_e \tilde{\rho}\cos\tilde{\alpha} + (1-K)k_v \tilde{\rho}_h \cos\tilde{\alpha}_h]\cos\tilde{\alpha} \\ &\quad + \dot{S}_\rho - K_\rho \dot{f}_t, \\ \dot{\tilde{\alpha}} &= -[K(k_q\tilde{\alpha} + k_e \sin\tilde{\alpha}\cos\tilde{\alpha}) \\ &\quad + (1-K)(k_\omega \tilde{\alpha}_h + k_v \sin\tilde{\alpha}_h \cos\tilde{\alpha}_h)] \\ &\quad + [K k_e \tilde{\rho}\cos\tilde{\alpha} + (1-K)k_v \tilde{\rho}_h \cos\tilde{\alpha}_h]\frac{\sin\tilde{\alpha}}{\tilde{\rho}+\beta} \\ &\quad - \frac{(\dot{S}_\alpha - K_\alpha \dot{f}_r)}{\tilde{\rho}+\eta}, \end{aligned} \tag{14}$$

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with $K = K(t)$. Reorganizing terms in Eq. (14), the delayed teleoperation system can be described by

$$\dot{\mathbf{x}} = \mathbf{K}(t)\, f(\mathbf{x}) + (\mathbf{I} - \mathbf{K}(t))\, g(\mathbf{x}, \mathbf{x_h}) + \mathbf{p}, \tag{15}$$

where

$$f(\mathbf{x}) = f\left(\begin{bmatrix}\tilde{\rho}\\ \tilde{\alpha}\end{bmatrix}\right) = \begin{bmatrix}-k_e\tilde{\rho}\,(\cos\tilde{\alpha})^2\\ -k_q\tilde{\alpha}\end{bmatrix}, \tag{16}$$

$$g(\mathbf{x}, \mathbf{x_h}) = g\left(\begin{bmatrix}\tilde{\rho}\\ \tilde{\alpha}\end{bmatrix}, \begin{bmatrix}\tilde{\rho}_h\\ \tilde{\alpha}_h\end{bmatrix}\right) = \begin{bmatrix}-k_v\tilde{\rho}_h\cos\tilde{\alpha}_h\cos\tilde{\alpha}\\ -k_\omega\tilde{\alpha}_h + k_v\cos\tilde{\alpha}_h\left(\dfrac{\tilde{\rho}_h\sin\tilde{\alpha}}{\tilde{\rho}+\eta} - \sin\tilde{\alpha}_h\right)\end{bmatrix}, \tag{17}$$

$$\mathbf{p} = \mathbf{p_1} + \mathbf{p_2},$$
$$\mathbf{p_2} = \begin{bmatrix}0\\ Kk_e\sin\tilde{\alpha}\cos\tilde{\alpha}\left(1 - \dfrac{\tilde{\rho}}{\tilde{\rho}+\eta}\right)\end{bmatrix} \le \begin{bmatrix}0\\ Kk_e\end{bmatrix}. \tag{18}$$

Note: $\mathbf{p_1}$ is defined in Eq. (13).

Next, we will analyze the stability of the system without perturbation, this is $p = \mathbf{0}$. Then, the system (15) can be represented by

$$\dot{\mathbf{x}} = \mathbf{K}(t)\, f(\mathbf{x}) + (\mathbf{I} - \mathbf{K}(t))\, g(\mathbf{x}, \mathbf{x}) + (\mathbf{I} - \mathbf{K}(t))\,[g(\mathbf{x}, \mathbf{x_h}) - g(\mathbf{x}, \mathbf{x})]. \tag{19}$$

Next, some properties will be deduced for their use in the stability analysis. If the definition of the induced norm is applied to the nonlinear function g and considering $|\dot{\mathbf{x}}| \le \gamma$, we can write that

$$|g(\mathbf{x}, \mathbf{x_h}) - g(\mathbf{x}, \mathbf{x})| \le |g|\,|\mathbf{x_h} - \mathbf{x}| \le |g|\, h\gamma. \tag{20}$$

In addition, from the closed-loop system represented by Eqs. (15), (16), and (17), the following expression can be written:

$$|\dot{\mathbf{x}}| \le |\dot{\tilde{\rho}}| + |\dot{\tilde{\alpha}}| \le \gamma \quad \text{with} \quad \gamma = k_e|\tilde{\rho}| + k_q|\tilde{\alpha}| + k_v\left(\frac{\eta+1}{\eta}\right)|\tilde{\rho}_h| + k_\omega|\tilde{\alpha}_h| \le \varepsilon\,(|\mathbf{x}| + |\mathbf{x_h}|), \tag{21}$$

where $\varepsilon > 0$ is the maximum value of $k_e, k_q, k_v(\frac{\eta+1}{\eta}), k_\omega$.

On the other hand, making $h = 0$ in Eqs. (15), (16), and (17), the nondelayed teleoperation system can be represented by a cascaded nonlinear system[15] given by

$$\begin{cases}\dot{\tilde{\rho}} = f_1(\tilde{\rho}, \tilde{\alpha}) = -(K(t)k_e + (1 - K(t))k_v)\,\tilde{\rho}(\cos\tilde{\alpha})^2,\\ \dot{\tilde{\alpha}} = f_2(\tilde{\alpha}) = -(K(t)k_q + (1 - K(t))k_\omega)\tilde{\alpha}.\end{cases} \tag{22}$$

Due to $(K(t)k_q + (1 - K(t))k_\omega) > 0$ for all t, then $\tilde{\alpha}$ in Eq. (22) is exponentially stable. In addition, since $(K(t)k_e + (1 - K(t))k_v) > 0$ for all t, then $\dot{\tilde{\rho}} = f_1(\tilde{\rho}, 0)$ is exponentially stable too. Besides, the interconnection term $(\cos\tilde{\alpha})^2$ is bounded and tends to 1 with an exponential rate of convergence. Therefore, the system given by

$$\dot{\mathbf{x}} = w(t, \mathbf{x}) = \mathbf{K}(t)\, f(\mathbf{x}) + (\mathbf{I} - \mathbf{K}(t))\, g(\mathbf{x}, \mathbf{x}) \tag{23}$$

is exponentially stable and from Lemma 1 of ref. [22] the following condition is verified:

$$\mathbf{x}^{\mathrm{T}}\dot{\mathbf{x}} = \mathbf{x}^{\mathrm{T}} w(t, \mathbf{x}) \le -\lambda\mathbf{x}^{\mathrm{T}}\mathbf{x}, \tag{24}$$

where λ is the exponential rate of convergence of the teleoperation system without time delay.

Now, a functional V to analyze the Lyapunov stability of the delay teleoperation system (19) is proposed as follows:

$$\begin{aligned}
V &= V_1 + V_2 + V_3 > 0,\\
V_1 &= \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{x},\\
V_2 &= \frac{1}{2}\varepsilon\,|g|\,\frac{h_m}{1-\tau}\,(1 - K(t))\int_{t-h}^{t}\mathbf{x}(\theta)^{\mathrm{T}}\mathbf{x}(\theta)\,\mathrm{d}\theta,\\
V_3 &= \frac{1}{2}\varepsilon\,|g|\,\frac{h_m}{1-\tau}\beta\int_{-h}^{0}\int_{t+\theta}^{t}\mathbf{x}(\psi)^{\mathrm{T}}\mathbf{x}(\psi)\,\mathrm{d}\psi\,\mathrm{d}\theta,
\end{aligned} \tag{25}$$

where $\dot{h} < \tau < 1$ and $h(t) \le h_m$ for all t. The derivative of V in Eq. (25) along the trajectories of the system (19), considering Eqs. (20), (21), (23), and (24), is the following one:

$$\begin{aligned}
\dot{V}_1 &\le -\lambda\mathbf{x}^{\mathrm{T}}\mathbf{x} + (1 - K(t))\,\varepsilon\,|g|\,h\left(\frac{3}{2}\mathbf{x}^{\mathrm{T}}\mathbf{x} + \frac{1}{2}\mathbf{x_h^{\mathrm{T}}}\mathbf{x_h}\right),\\
\dot{V}_2 &= \frac{1}{2}\varepsilon\,|g|\,\frac{h_m}{1-\tau}\left[-\dot{K}\int_{t-h}^{t}\mathbf{x}(\theta)^{\mathrm{T}}\mathbf{x}(\theta)\,\mathrm{d}\theta + (1 - K(t))\left(\mathbf{x}^{\mathrm{T}}\mathbf{x} - (1-\dot{h})\mathbf{x_h^{\mathrm{T}}}\mathbf{x_h}\right)\right],\\
\dot{V}_3 &= \frac{1}{2}\varepsilon\,|g|\,\frac{h_m}{1-\tau}\beta\left[h\mathbf{x}^{\mathrm{T}}\mathbf{x} - \int_{t-h}^{t}x(\theta)^{\mathrm{T}}x(\theta)\,\mathrm{d}\theta\right].
\end{aligned} \tag{26}$$

Considering that

$$\begin{aligned}
&\frac{1}{2}(1 - K(t))\,\varepsilon\,|g|\left(h - h_m\frac{1-\dot{h}}{1-\tau}\right)\mathbf{x_h^{\mathrm{T}}}\mathbf{x_h} < 0\\
&\frac{1}{2}\varepsilon\,|g|\,\frac{h_m}{1-\tau}\left[\int_{t-h}^{t}\mathbf{x}(\theta)^{\mathrm{T}}\mathbf{x}(\theta)\,\mathrm{d}\theta\right](-\dot{K} - \beta) < 0
\end{aligned} \tag{27}$$

because $(h - h_m\frac{1-\dot{h}}{1-\tau}) < 0$ and $-\dot{K} - \beta < 0$, then $\dot{V}$ can be represented by

$$\dot{V} \le \left[-\lambda + \frac{3}{2}\varepsilon\,|g|\,h\left((1 - K(t)) + \frac{h_m\beta}{3(1-\tau)}\right)\right]\mathbf{x}^{\mathrm{T}}\mathbf{x}. \tag{28}$$

Finally, the system (19) is exponentially stable if

$$c = -\lambda + \frac{3}{2}\varepsilon\,|g|\,h\left((1 - K(t)) + \frac{h_m\beta}{3(1-\tau)}\right) < 0, \tag{29}$$

with an exponential rate of convergence ζ depending on c (Theorem 1 of ref. [22]). If the control scheme makes

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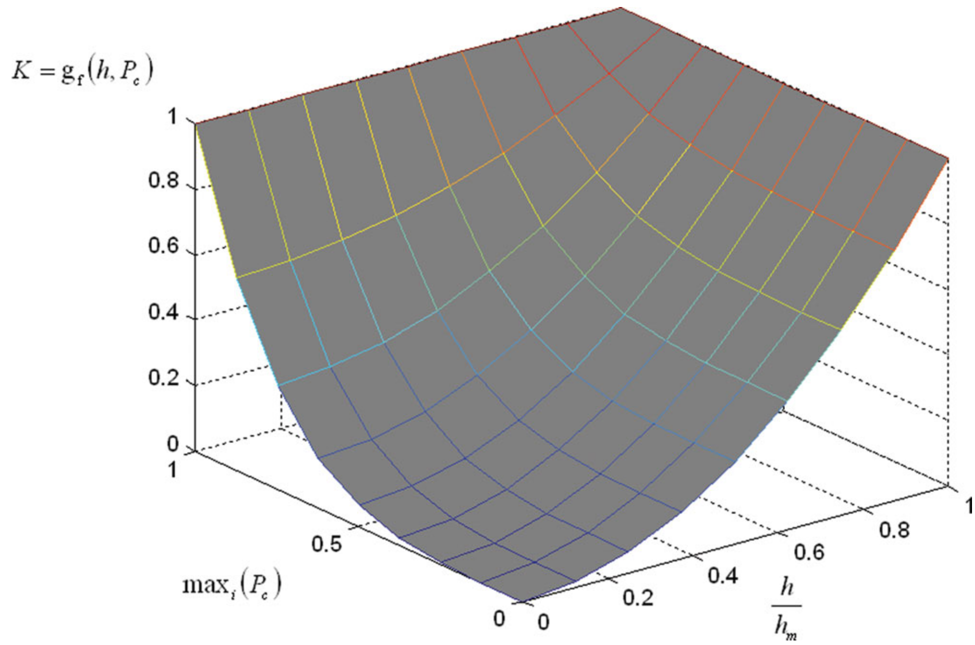

Fig. 7. (Colour Online) Proposed function to fuse commands.

Eq. (27) be true for all t being the perturbation bounded $p = p_1 + p_2 \leq \delta$, then the delayed teleoperation system will be ultimately bounded to a ball of size B given by $B < \sqrt{0.5\frac{\delta}{\theta}}\zeta^{-1}$ (Lemma 5.2, p. 213 of ref. [10]), with an exponential rate of convergence γ given by $\gamma = (1-\theta)\zeta$, where $0 < \theta < 1$ is a positive arbitrary constant.

5. Commands Fusion

In this section, a function $K(t)$ to join the control signals provided by the human operator and a remote controller is proposed. The stability analysis shows in Eq. (29) that if a high priority of the remote controller (K near 1) is kept, then a good stability is obtained. But this condition is very conservative for small and medium delays since the full capability of the users would not be used. In addition, the current situation is not taken into account. For example, the use of $K = 1$ constant, in spite of carrying out a stable motion of the robot, will produce permanently differences between the user's command (linear and angular velocities) and the real velocity of the mobile robot. This will generate a significant difference between the motion carried out by the mobile robot and the robot motion that the human operator wants for it.

In this paper, a strategy to assign the value of $K(t)$ is proposed, where the delay and current driving of the user are taken into account. The adopted criterion to design $K(t)$ is based on the effect produced by the time delay on the stability and the current situation measured through the crash probability P_c calculated online for each obstacle i. Human factors affect the crash probability, for example, in case of a user with experience driving the robot by an environment with obstacles, the crash probability will be less, and therefore, $K(t)$ will be such that the control action computed by the proposed scheme will tend to the command generated by the human operator. On the contrary, when the user has low experience or produces errors by distraction, fatigue, etc., the crash probability will be greater, and then, $K(t)$ will have a value such that the proposed scheme will prioritize more the remote controller. The proposed scheme tries assuring a good robustness level of the delayed teleoperation system in front of possible collisions, but keeping a high level of participation (perception and action) of the human operator.

A function depending on the time delay and the crash probability to join the human operator and a remote controller is proposed as follows:

$$K(t) = g_f(h, P_c) = \max_i (P_c)^m + \left(\frac{h}{h_m}\right)^n - \max_i (P_c)^m \left(\frac{h}{h_m}\right)^n, \quad (30)$$

where $m, n \geq 1$ are positive integer numbers. Figure 7 shows the function g_f in 3D setting $m = 4$ and $n = 2$, where the time delay as well as the current context measured by using the crash probability are considered.

6. Teleoperation Experiments with Time-Varying Delay and Force Feedback

This section shows experiments of teleoperation of a mobile robot using the proposed control scheme, which joins the human operator's commands and a remote controller, based on a fusion function (30) and an enhanced predictor (4), both depending on the time delay and the crash probability.

6.1. Crash probability

The implemented algorithm to calculate on line a value representative of the collision probability is based on the information measured by a laser sensor on board of the mobile robot. Figure 8 shows a block diagram of how the algorithm to measure the crash probability works. Such

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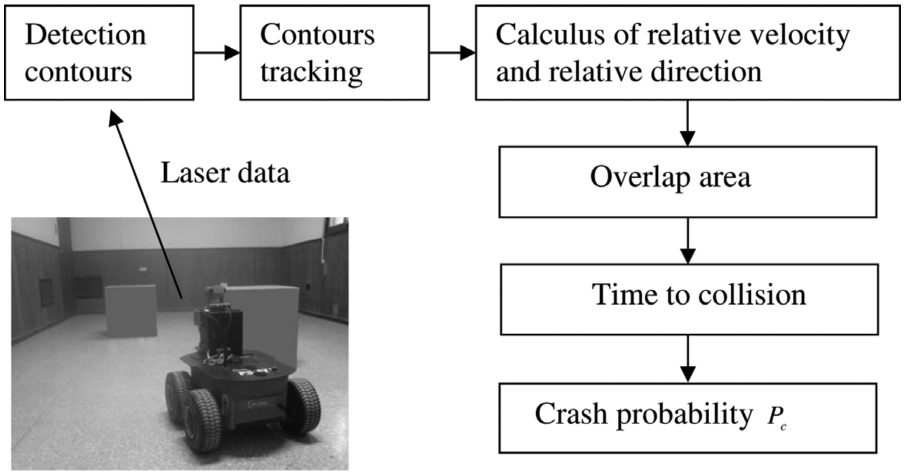

Fig. 8. Crash detection algorithm.

algorithm is based on detecting contours with the laser data and tracking them in order to calculate the relative direction and relative velocity between the mobile robot and the obstacles (detected contours). Then, the overlap area is calculated for each obstacle taking into account the relative motion direction between it and the mobile robot. In case of obtaining an overlap area different to zero, the time to collision is computed using the relative velocity. Finally, the crash probability for each obstacle is calculated as the overlap area divided by the time to collision.

6.2. *Experiments*

The experiment consists of a user driving a mobile robot through a delayed teleoperation system in order to achieve a position about 5 m in a straight line from the start position of the robot avoiding collisions with a box placed in front of it. A Pioneer 3DX mobile robot (www.activmedia.com), which has a differential drive, is used. It is equipped with a video camera, laser sensor, encoders, and computer onboard with Wi-Fi connectivity. The used laser is made by SICK and has a range of π radians with a resolution of $\frac{\pi}{180}$ radians. The human operator perceives delayed visual and force feedback and generates velocity commands through a steering wheel made by Genius and a joystick manufactured by the INAUT, University of San Juan. Both devices have a potentiometer-type sensor to measure their angular position. The joystick includes a DC electric motor of 12 V and 2.5 A controlled by a PIC 18F4550 microcontroller with a sampling time of 2 ms.

The local site and the remote site are an office and a classroom at the San Juan University, respectively, in Argentina; and they are linked via Intranet using the IP/UDP protocol. In this case, the delay added by the Intranet is very small, so we increase it using FIFO buffers of time-varying size.

On the other hand, the parameters of the remote controller are set to $k_e = 1\,\mathrm{m/s}$ and $k_q = 0.5\,\mathrm{rad/s}$ for the position controller, $K_\rho = 1.25\,\mathrm{m/N}$ and $K_\alpha = 0.25\,\mathrm{rad/N}$ for the impedance control, $k_1 = 2\,\mathrm{s}$ and $k_2 = 1\,\mathrm{s}$ in the predictor, $k_3 = 1\,\mathrm{N}$ and $k_4 = 1\,\mathrm{N/m}$ for the calculus of the fictitious force, $\eta = 0.3\,\mathrm{m}$, and $m = 4$, $n = 2$, and $h_m = 4\mathrm{s}$ are set to compute $K(t)$. The time delay is not known *a priori*; therefore, h_m is reasonably set to assure that $h_m \geq h(t)$ for all t. Besides, the mobile robot has two PID velocity controllers (on board) to set the linear and angular velocity of the robot, which sends information from its sensors and receives velocity references every 50 ms. However, the PID controllers run in a time cycle faster.

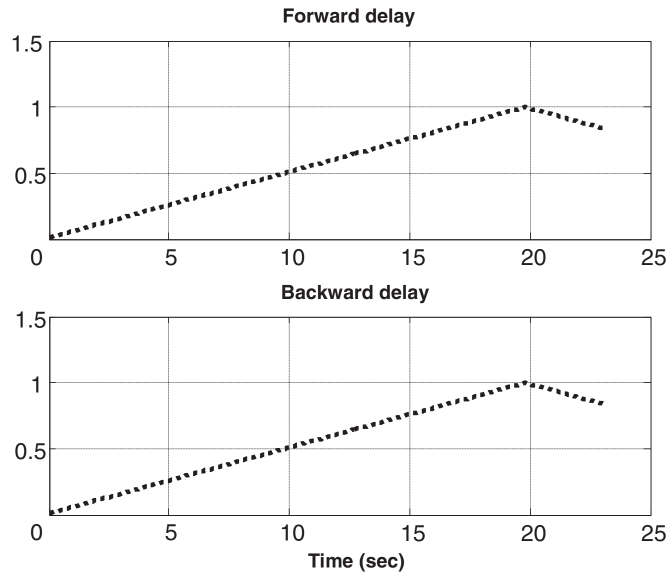

Fig. 9. Time-varying delay in experiment 1.

The users were trained before the experiments by using the simulator *MobileSim* created by the *Player/Stage/Gazebo* project (http://playerstage.sourceforge.net). The training consists in driving a mobile robot without time delay in order that the user uses the interface formed by the steering wheel and the joystick with force-reflection correctly.

Figure 11 shows the trajectories followed by the mobile robot teleoperated by a user for different time-varying delays (symmetric and asymmetric), which are shown in Figs. 9, 10, and 12. Figure 12 shows how the user is helped by the proposed control scheme, there it is possible to appreciate the user's command on the remote site, the velocity of the mobile robot, the force feedback felt by the user, the crash probability, and $K(t)$.

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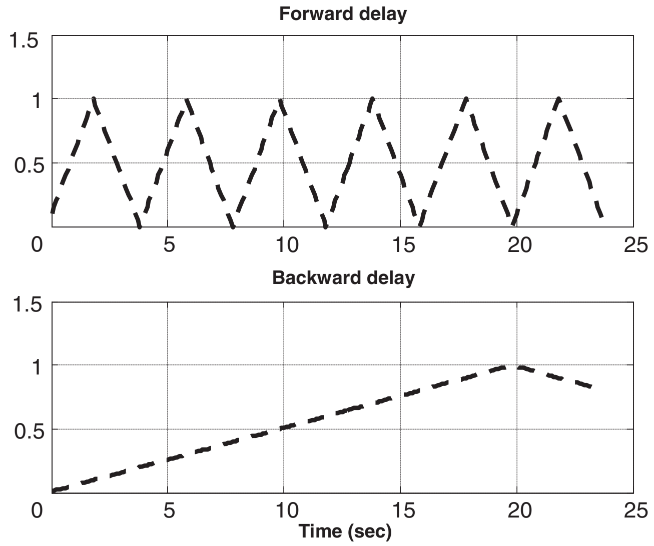

Fig. 10. Time-varying delay in experiment 2.

Figure 12 shows the evolution in time of $K(t)$, it notably increases when the collision probability is big. When $K(t) = 1$, the assisted control is applied totally. Instead, when $K(t) = 0$, the human operator teleoperates the mobile robot directly. The assisted control provides a stable motion of the mobile robot avoiding collisions too. For example, in about 3 s, the velocity of the robot decreases although the human operator keeps constant his command of linear velocity because there is a high collision probability. Similarly, between 5 and 10 s, it is possible to appreciate that the angular velocity of the mobile robot does not follow exactly the command produced by the human operator. In this case, the user sees and feels with delay the interaction between the mobile robot and the box (Fig. 11), which makes him keep a value of the angular velocity for too long, which would lead to a very open curve. However, the assisted control acts to avoid an inadequate integration of commands of angular velocity. In addition, the assisted control helps the human operator when the time delay is significant even though the collision probability is low.

The force feedback allows enhancing the user's perception about the remote environment; in this case, the user feels the closeness of the obstacle, while the time delay and the crash probability are used to modify the user's command. It is important to remark that the goal and remote environment are not known, but they are online estimated by the designed control scheme.

The experimental results show a good performance of the designed teleoperation system applied to teleoperation of mobile robots with force feedback with respect to various time-varying delays including symmetric and asymmetric delays as well as several variation rates and amplitude values.

7. Conclusions

In this paper, a control scheme based on the design of a predictor and commands fusion applied to the teleoperation of a mobile robot with time-varying delay and force feedback has been proposed. The stability analysis made showed that if the time delay is big, then a high priority given to the remote controller is the apparent best choice, but the capability of the users would not be completely used and the current context is not considered. Instead, the proposed control scheme uses a commands fusion between the user and a remote controller and a predictor, both depending on the

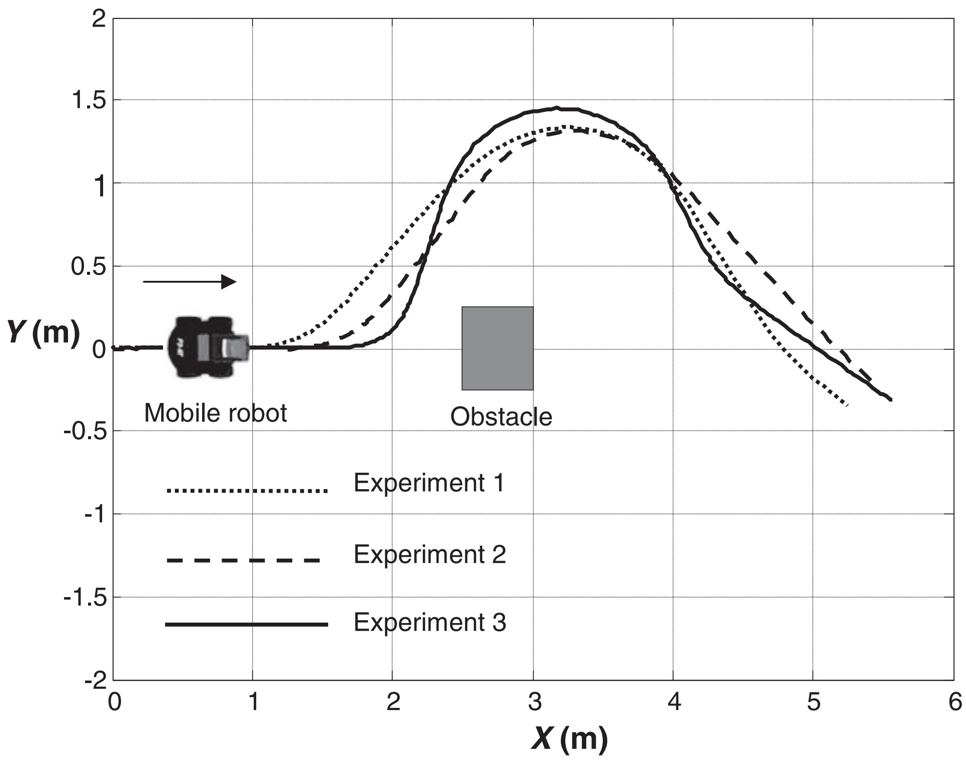

Fig. 11. Trajectories followed by the mobile robot teleoperated for different time delays.

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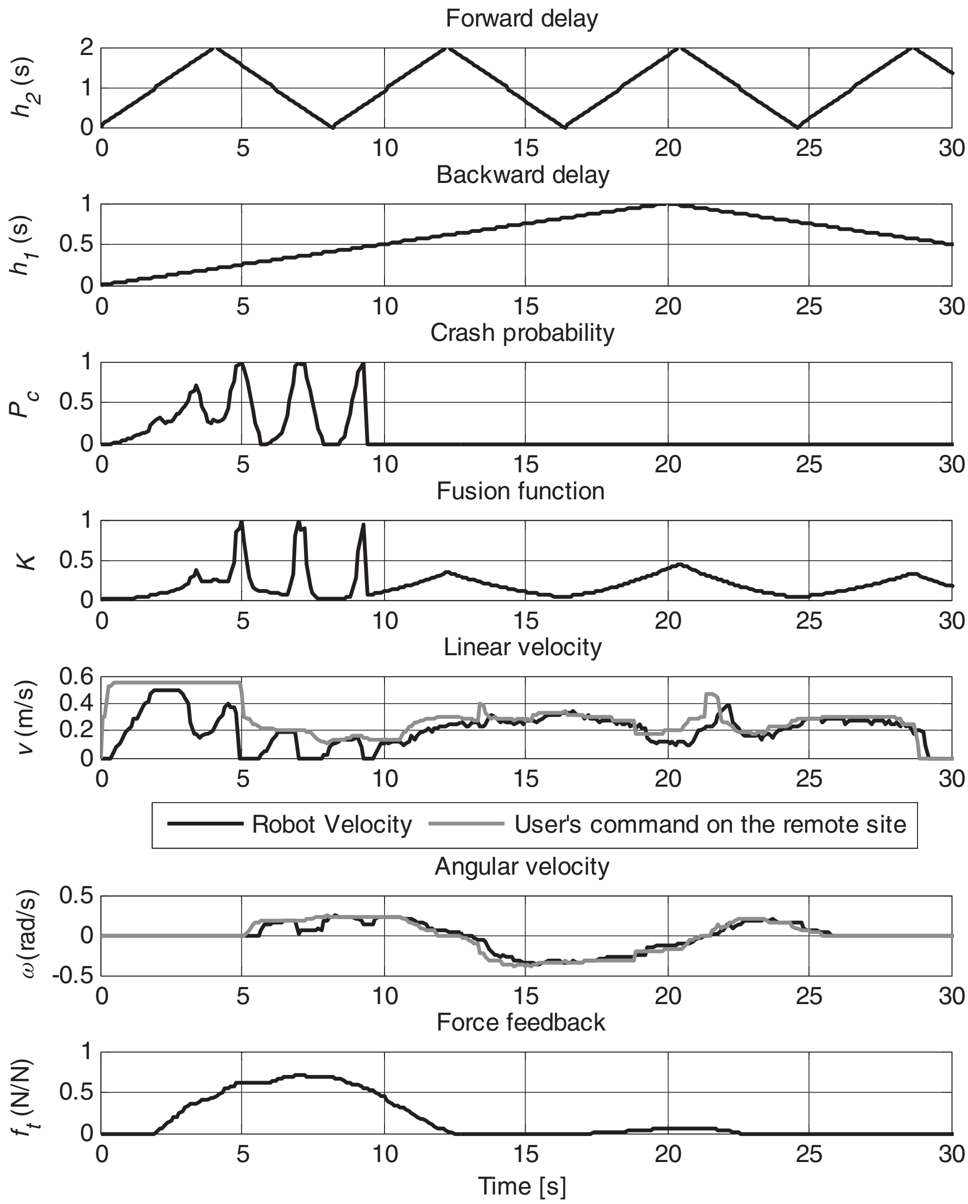

Fig. 12. User's command, force feedback, crash probability, time delay, $K(t)$, and control action for experiment 3.

time delay and the crash probability in order to get a trade-off between the robustness in front of possible collisions and the participation level of the human operator taking advantage of his perception, decision, and action. Several experiments have been carried out to test the real performance of the designed teleoperation system.

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