Force Feedback Stabilization for Remote Control of An Assistive Mobile Robot

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Abstract— **In this paper, we consider a bilateral control of an assistive mobile robot over communication channels with constant/variable time delays. The mobile robot is used for exploring a domestic environment. The main purpose of the present work is to help the human in controlling better the slave robot. In addition, the proposed control scheme improves the operator perception of the remote environment. The human-operator can actively control the mobile robot, using its intrinsic sensors, and "feel" the robot's environment. The haptic device is used like a joystick and controls the linear velocity and heading angle of the mobile robot. Many experiments have been performed to validate the proposed control scheme, and to show, in the same time, the importance of the force feedback in such applications and accessibility situations : doorways, obstacle exploration, wall tracking, etc.**

I. INTRODUCTION

The increasing number of elderly people, especially with pathologies such as Alzheimer disease, is becoming an important issue in Europe. It is more and more difficult and expensive to assure long term hospitalization for these people, so they stay at home as long as possible. There are two aspects to make that possible: security of the person and cognitive stimulation. The aim of the European CompanionAble project is to assist the people with Mild Cognitive Impairment (MCI) and their families in those situations, in the context of ambient assisted living. Thus, a robot is used to give the possibility to caregivers and relatives to have distant interaction with the user. The purpose of the robot is not to remove the human presence around the person, but to ease his caring.

Teleoperated mobile robots are an important tool in the exploration of unknown and risky environments. Bomb disposal robots [13] or robots used for exploration of underwater environments [16] are two common applications. However, the motions of these mobile robots are usually controlled by human operators using passive sensors, such as the camera.

Low-cost force feedback devices are incorporated in these applications because of their success and their simplicity of use. Many of these interfaces, like the haptic one, appear in many research areas of robotics and recently in the field of mobile robot teleoperation [8], [10]. These mobile robots operate environments physically. Haptic devices help to improve the operator's perception of the environment and give users the illusion of "feeling" the robot workspace, improving, among others, his/her ability to avoid obstacles and reducing the number of collisions [11].

These applications find all their interest in slaves remote environments, namely the human intervention of a competent person on one or more "remote sites". But this distance induces major problems of stability and transparency due to communication delay. To ensure the stability of haptic interaction, some control schemes have been proposed. The first is a simple transposition of the control scheme used in bilateral teleoperation, [7]. The second type of control schemes is generally passive and, unfortunately, degrade significantly the transparency of the haptic rendering, [10]. This last property is essential to feel details interactions between mobile robot-slave environment (corners, obstacles shape, etc.)

Compared to classic bilateral teleoperation, few schemes have been proposed for mobile robots [8], [10]. The time delays problem has been addressed in some of these works, unfortunately, the authors neglect the fidelity of haptic rendering (crucial aspect) to the benefit of stability due to passivity based control and the impact of variable time delay on these properties (stability and transparency). In contrast, based on predictive control [15], our proposed control scheme supports variable / constant time delays, and ensures, under some assumptions, a good balance between stability and transparency (no need for any transformation process based on wave variables technique [4]).

The rest of the paper is organized as follows: sections III and IV highlight the description and modeling the whole interaction Human-Device-Robot. The next two sections are devoted to the adopted control scheme and the stability analysis. The paper ends by a large section on simulation and experimentation results. Discussions and the traditional conclusion wrap up this work.

II. SYSTEM DESCRIPTION

An overview of the mobile robot haptic teleoperation system is illustrated in Figure 1. It consists of two sides: the master side, which contains the haptic device and the master station and the slave side, which contains the mobile robot and a slave robot server/environment.

Generally, haptic feedback is achieved by transmitting either real contact force (measured by force sensors) or artificial/virtual force computed according to the distance between the robot and obstacles (measured by sonar). However, in some applications, such extra sensors may be too costly or ineffective (e.g. contact outside sensing zone). Their failures may also result in erroneous force feedback or even unstable system behaviors [10]. For our application,
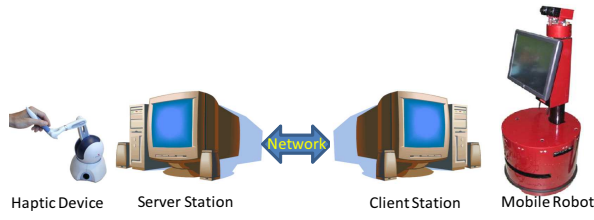
Fig. 1. Teleoperation System Scheme

the haptic feedback is achieved by using only the basic navigation sensors.

The mobile robot that was used is named *Lina* and it is a circular, two driving wheels, robot (see experiments subsection for more description).

III. SYSTEM MODELING

A. Mobile Robot Modeling

Based on [6], the dynamics of a non-holonomic two wheeled mobile robot is given by:

$$D(x)\begin{pmatrix} \dot{v} \\ \ddot{\phi} \end{pmatrix} + Q(x,\dot{x})\begin{pmatrix} v \\ \dot{\phi} \end{pmatrix} = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} + \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} \quad (1)$$
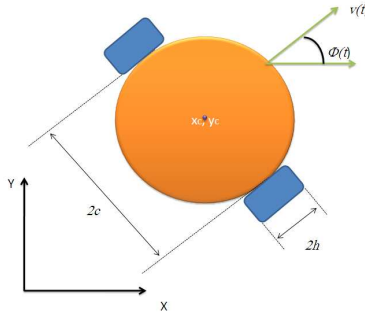

Fig. 2. References and Parameters of the mobile robot geometry

Where $v(t)$, $\phi(t)$ are the linear velocity and the heading angle of the mobile robot, $x = (x_c, y_c, \phi, \theta_r, \theta_l)$ is the 5-DOF configuration of the robot with (x_c, y_c) and (θ_r, θ_l) are the position of the robot gravity center and the rotation of the right/left wheels, (δ_1, δ_2) are the external forces/torques acting on the robot, and $(u_1, u_2) = (\frac{c}{h}(u_r + u_l), \frac{c}{h}(u_r - u_l))$ are the controls with (u_r, u_l), h, and c being the angular torques of the right and left wheels, the radius of the wheels, and the robot body radius, respectively (See Figure 2).

Then, the evolution of the 5-DOF mobile robot can be computed by solving the (reduced) 2-DOF dynamics, equation 1, and the following kinematic constraint:

$$\begin{cases} \frac{dx_c}{dt} = v \cdot \cos\phi \\ \frac{dy_c}{dt} = v \cdot \sin\phi \\ \frac{d\phi}{dt} = \dot{\phi} \\ \frac{d\theta_r}{dt} = \frac{v+c\dot{\phi}}{h} \\ \frac{d\theta_l}{dt} = \frac{v-c\dot{\phi}}{h} \end{cases} \quad (2)$$

The mobile robot dynamic model can be used for several applications, such as a semi-experiment to test the control laws before tests with real robots (what we have achieved, but not discussed in this paper), reconstruction of the slave environment, the identification of dynamic parameters of robots with special structure, etc.

B. Haptic Device Modeling

The haptic devices are much less bulky than the master arms used in teleoperation. Thus, almost all of these devices are "human arm scale" and allow effortless handling (weight compensation and inertia), in an appropriate workspace. On the other hand, the motion transmission is done by systems with very low friction. In addition, a small workspace limits the accelerations and velocities that can be made by the operator, thus inertial effects are neglected.

Taking into account the previous assumptions, it becomes possible to model, in a linear way, a large class of haptic devices as an apparent mass and/or inertia that the operator manipulates inside the device's workspace under a small apparent friction.
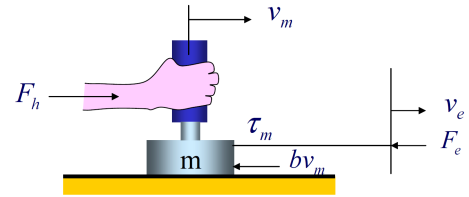

Fig. 3. 1-DOF Linear Haptic Device.

We consider a 3-DOF haptic joystick as the master device. Only 2-DOF are used for the control of the mobile robot (planar motion with respect to x and y end-effector references). The device dynamic model is governed by following equation:

$$m_m\begin{pmatrix} \ddot{x}_m \\ \ddot{y}_m \end{pmatrix} + b_m\begin{pmatrix} \dot{x}_m \\ \dot{y}_m \end{pmatrix} = F_h + \tau_m \quad (3)$$

Where m_m, b_m are the apparent mass and friction of the haptic device, x_m, y_m are end-effector displacements, F_h, τ_m being the exerted human force and control input (torque), respectively. On Figure 3, v_e (velocity) and F_e (force) represent the input/output of the interaction between human operator and the slave environment.

IV. CONTROL DESIGN

This section addresses a general control design for a time-delayed haptic interaction with real/virtual environments. Here a stable predictive-like approach is adopted based on the Smith predictor technique, [5], [14]. The major difference with this technique lies in the fact that we do not need to estimate the time delay or know its fluctuations. Therefore, our controller applies to constant or time-varying delays cases without any adaptation.

where $M(s)$ is the haptic device transfer function, $C(s)$ is local controller (virtual coupling, [12]), τ_i are respectively
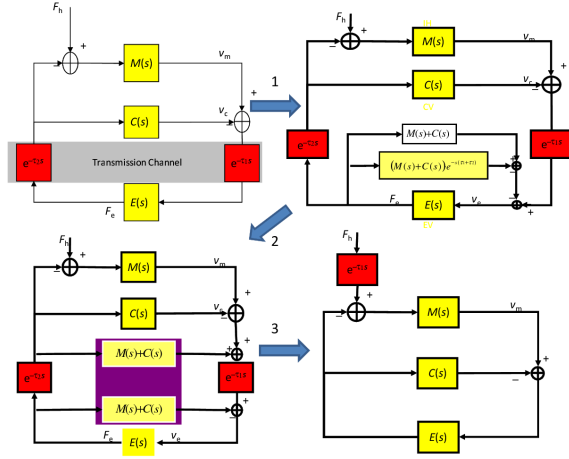
Fig. 4. Design steps of predictive control scheme (PCS): (a) Delayed haptic interaction without PCS, (b) Smith Predictor integration, (c) Modified Smith Predictor (information on delay size unnecessary) and (d) final equivalent control scheme.

upwards and downwards time delays (constant on the figure) and $E(s)$ represent the robot and its environment. F_e is the slave environment computed force, F_h is the operator applied force on the device.

Figure 4 illustrates the different steps encountered in order to achieve the final version of the controller. Indeed, the first step was to apply the principle of the Smith predictor model around the slave environment. This idea was quickly ignored because the difficulty in predicting the behavior of the robot and its dynamic environment. Therefore, we applied the same principle around the master device (the model of the master device should be linear and well known). To succeed in this latest development, we must know the size of the delay (if constant) and even more difficult to predict the fluctuations (if variable). This second case is very interesting, but unusable if we use a non-deterministic communication protocol without an appropriate control law.

To overcome this difficulty, we move the second delayed branch predictor on the other side (slave site). The result consists of a stable controller requiring only knowledge of the haptic device model. This evolution suggests that stability in the case of variable time delay is maintained, that we prove in the next section below.

V. STABILITY ANALYSIS

The present controller constitutes a generic result and can be applied for virtual or real haptic environments.

Figure 5 represents two interconnected systems defined respectively by their transfer functions G_1 and G_2. The respective inputs are e_1 and e_2 and the outputs are y_1 and y_2. These parameters are governed by the following equations system:

$$\begin{cases} u_1(t) = e_1(t) - y_2(t) \\ u_2(t) = e_2(t) + y_1(t) \end{cases} \tag{4}$$

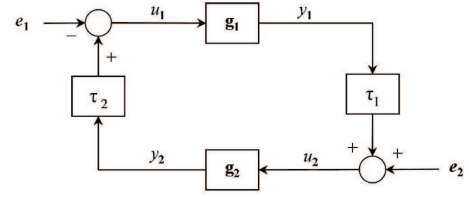Where u_1 and u_2 are the control signals.

Fig. 5. Closed loop of the interconnected systems

If τ_i are zero, the passivity of the present interconnected system depends on the passivity of each system, see [9].
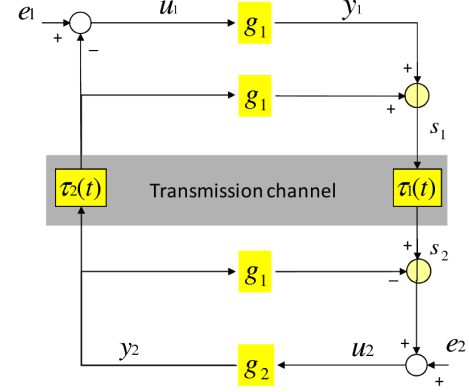

Fig. 6. Proposed control scheme based master device model g_1

The entire interconnected system (Figure 5) can be stabilized, using a control based on the process model G_1 or G_2, as shown in Figure 6.

The proof is quite simple. The equations describing the system are given by:

$$\begin{cases} u_1(t) = e_1(t) - y_2(t) * h(t - \tau_2(t)) \\ u_2(t) = e_2(t) + y_1(t - \tau_1(t)) \\ + y_{11}(t) * h(t - \tau_1(t)) - y_{12}(t) \end{cases} \tag{5}$$

where,

$$\begin{cases} y_{11}(t) = (y_2(t) * h(\tau_2, t)) * g_1(t) \\ y_{12}(t) = y_2(t) * g_1(t) \end{cases} \tag{6}$$

$h(\tau_i, t)$ represents the the impulse response of the transmission channel (τ_i may be variable). If we assume that $g_1(t)$ is known and linear, the output equation of $s_1(t)$ becomes :

$$s_1(t) = y_1(t) + y_{11}(t) = \\ u_1(t) * g_1(t) + (y_2(t) * h(\tau_2, t)) * g_1(t) \tag{7}$$

By substituting the value of $u_1(t)$ into (5), we obtain :

$$s_1(t) = (e_1(t) - y_2(t) * h(t - \tau_2(t))) * g_1(t) \\ + (y_2(t) * h(\tau_2, t)) * g_1(t) \tag{8}$$

This can be simplified as:

$$s_1(t) = e_1(t) * g_1(t) \tag{9}$$

By replacing this equation into $s_2(t)$ formula, we have :

$$s_2(t) = (e_1(t) * g_1(t)) * h(\tau_1, t) - y_2(t) * g_1(t) \quad (10)$$

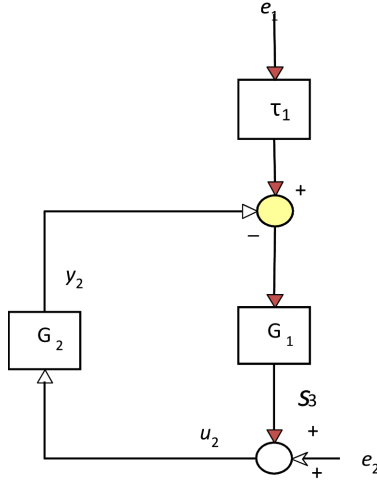This system can be represented by the new control scheme illustrated by Figure 7.

Fig. 7.   Equivalent control scheme

Now, we shall prove that if the transfers g_1 and g_2 are stable, then the entire system is also stable.

Let's consider two separate cases: constant and variable delay.

In the first case, the impulse response of $h(\tau_1, t)$ becomes a linear operator on which we can apply the following property :

$$(f * g)_\tau = f_\tau * g = f * g_\tau \quad (11)$$

Hence, the expression of $s_2(t)$ will be simplified to:

$$s_2(t) = (e_1(t - \tau_1) - y_2(t)) * g_1(t)) \quad (12)$$

As transfers g_1 and g_2 are assumed linear, then the closed loop system is passive (stable).

When the time delays are variable, the previous system cannot be simplified because of $f_{\tau(t)} * g \neq f * g_{\tau(t)}$, and we have :

$$\begin{bmatrix} s_2 \\ u \end{bmatrix} = \frac{1}{1 + G_1 G_2} \begin{bmatrix} 1 & -G_1 G_2 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} s_{1\tau_1} \\ e_2 \end{bmatrix} \quad (13)$$

where $s_{1\tau_1}$ is the first delayed output and constitutes the input of the closed loop system $G_1 G_2$ and $u = s_2 + e_2$. In this case, the system stability is guaranteed because $\frac{1}{1+G_1 G_2}$ is supposed stable. We suppose that $g_2(t)$ represents the mobile robot and its slave environment.

VI. FORCE FEEDBACK STRATEGY

As stated before, the force feedback is computed according to the distance, X_i, between the robot and obstacles (measured by sonars). In order to computer the necessary force to alert the human operator on the presence of obstacles

or an upcoming impact, we set two thresholds distances from which the operator feels two different forces (Figure 8). These thresholds are defined as follows:

$$\begin{cases} X_{wall} \leq X_i \leq X_{spring} \rightarrow F_i = k_s(X_i - X_{spring}) \\ 0 \leq X_i \leq X_{wall} \rightarrow \\ F_i = k_w(X_i - X_{wall}) + k_s(X_{spring} - X_{wall}) \end{cases} \quad (14)$$

Where X_{spring} is the first threshold position limiting the "spring" zone, X_{wall} is the second threshold position limiting the "wall" zone, k_w and k_s are respectively stiffness coefficients calculated depending on the zone properties.
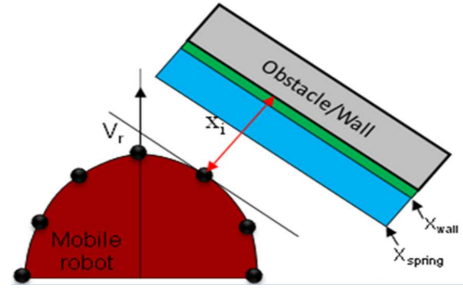

Fig. 8.   Threshold distance limit between mobile robot and obstacle

A. Joystick Effect

For security reasons and to preserve the mobile robot, we added a permanent force feedback $F_{0/(x,y)}$ so that it repositions the haptic end-point on its neutral position or neutral zone. This property is important if the operator releases the haptic arm, the end-point quickly returns to the neutral position and the robot stops its progression.

$$F_{0/(x,y)} = -k_0 X_m \quad (15)$$

where k_0 is a small stiffness.

The neutral position may be extended to a neutral *zone*, in order to ignore minute hand movements (shaking), thus preserving the life of the engines.
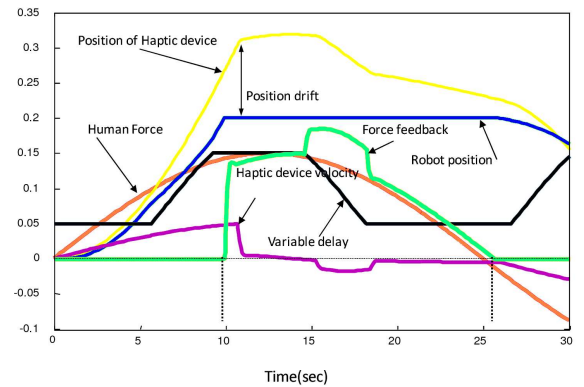

Fig. 9.   Simulation results under variable time delay

VII. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

In this section we present simulation results of the used predictive control. The haptic display parameters are a felt-mass of $m = 0.2kg$ and a motion felt-friction of $b = 3Ns/m$. The simulated virtual contact is performed between a rigid virtual probe and virtual walls of stiffness $K_e = 1000N/m$. Time delays, $\tau_1(t)$ and $\tau_2(t)$, have the same shape.

Figure 9 shows the result of the haptic interaction under time-varying delay ($\tau_1(t)$ variation is plotted on the same figure). In this case, the simulation shows a globally stable behavior of the system. Therefore, the dynamic of $\tau_1(t)$ affects the response behavior of haptic feedback. Indeed, Figure 9 shows clearly that when a transition occurs between different $\tau_1(t)$ behaviors, i.e. between varying and constant delays, the force feedback response switches respectively between two different system behaviors. The transitions seem to be abrupt but do not affect the overall stability of the system.

The control scheme robustness, against error estimation of model parameters, will not be studied in this paper.

B. Experimental Results

All the experiments have been performed on a real robot. Lina (Figure 1) is a circular two driving wheels robot. Its maximum linear speed is $1.2m/sec$ and $4rad/sec$. It is equipped with 12 ultrasonic sensors all around its body, one each $30°$. For the present experimentations, only the seven frontal sensors are used. They are labeled x_0 to x_6. The robot uses a Wifi connection for communication between control units.

We have validated our model in three spatial situations encountered in indoor environments: movement towards a wall, following a corner wall and driving between two obstacles. Due to the reduced paper space, only a few results have been presented here.

For each of these spatial situations, four kinds of feedbacks to the human operator have been performed. In the first one, no force is sent to the user (not represented here). This situation is called "SE". It is a reference experiment, in which forces are computed but not fed back to the operator. That will be a mean to compare this situation with the others. In the second situation, a force is fed back to the operator, without transmission delay (Figure 10). This situation is called "SR". The third situation corresponds to a force sent with a delay and no stabilization control is applied. This situation is called "RNC". The last situation corresponds to a force sent to the user under various size of time delays (Figure 11).
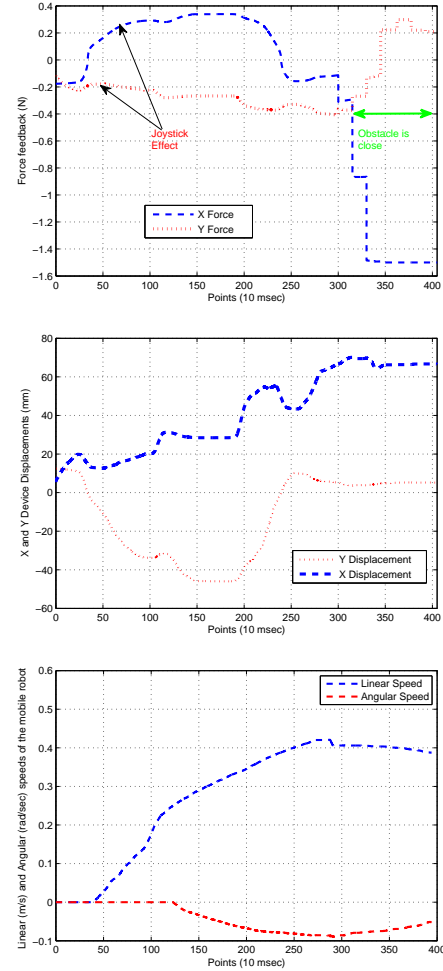

Fig. 10. Experimental Results of the Mobile Robot approaching a wall without Time Delay $\tau_i=0$: (a) X and Y Force feedback, (b) X and Y device displacements and Linear and angular speeds of the Mobile Robot

Four subjects, aged between twenty-five and thirty, have taken part to the experiment. They had about twenty minutes to get familiar with the application. This learning was conducted without transmission delays.

Figure 10 illustrates the behavior of the whole interaction under ideal conditions (i.e. time delays are zero). The mobile robot is controlled to move closer to a wall. In this figure, we note at the beginning of the experiment a non-negligible force feedback, which corresponds to the joystick effect, necessary to return the haptic device in its neutral position.

In figure 11, the mobile robot navigates in a complex environment where it must pass between two obstacles. The experiment is performed under a variable time delays with mean at 200 $msec$. The curves show a stable force feedback. But, because a large time delay and a speed control technique of the mobile robot, human operators feel compelled to slow down to pass away the obstacles safely (a small linear velocity of the mobile robot).
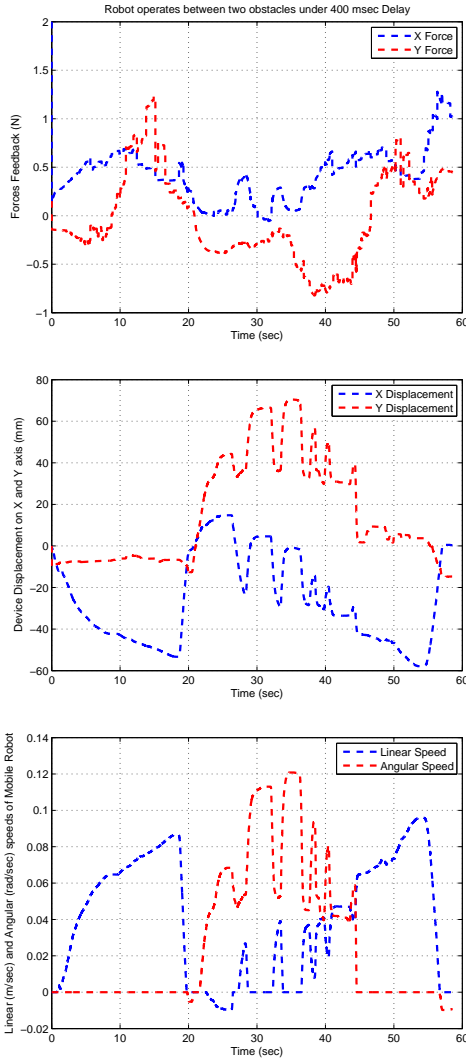
Fig. 11. Experimental Results of the Mobile Robot operates between two obstacles, under varying Time Delays : (a) X and Y Force feedback, (b) X and Y device displacements and Linear and angular speeds of the Mobile Robot

VIII. CONCLUSION

In this paper, an assistive robot teleoperation system with haptic interface has been presented. The goal considered is that of remotely driving a mobile robot to perform an exploration task for a domestic environment.

The proposed control scheme uses the X-Y displacements of the haptic device as a speed control for the mobile robot. This scheme offers a very intuitive manipulation. For security reasons we have implemented a standard joystick control to preserve the robot's motors from damages.

The structure of the controller leads to interesting extensions that:

- avoid the estimation of time-delay (variable or constant);
- make a straightforward extension to time-varying delay (without any adaptation);
- the mobile robot behavior knowledge is not necessary.

The first experimental results presented above have also suggested that force feedback helps the user to pilot the robot amongst obstacles, in particular, in the case of low quality video feedback (due to overexposure for example). We plan to run an experiment to attest that with statistical results, to measure the influence of delays and to evaluate the efficiency of delay correction we will develop.

Future work will deal with the creation of the remote environment geometry in real-time and the contribution of force feedback in the rapid completion of tasks.

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