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Adaptive Impedance Control in Haptic Teleoperation to Improve Transparency under Time-Delay

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Abstract— **This paper proposes the application of an adaptive impedance control scheme to alleviate some of the problems associated with the presence of time delays in a haptic teleoperation system. Continuous on-line estimation of the remote environment's impedance is performed, and is then used as a local model for haptic display control. Lyapunov stability of the proposed impedance adaptation law is demonstrated. A series of experiments is performed to evaluate the performance of this teleoperation control scheme. Two performance measures are defined to assess transparency and stability of the teleoperator. Simulation results show the superior performance of the proposed adaptive scheme, with respect to direct teleoperation, particularly in terms of increasing the stability margin and of significantly ameliorating transparency in the presence of large time delays. Experimental results, using a Phantom Omni as the haptic master device, support this conclusion.**

I. INTRODUCTION

Teleoperation, as a general term in robotics, involves all the methodologies and technologies enabling a human operator to perform from a distance a task through the use of an intermediate mechatronic (robotic) system. Telemanipulation control of a remote manipulative task (besides its fascinating character related to the notion of extending human capabilities, by means of some tool, beyond usual space or time limits) can prove extremely beneficial in cases where human intervention is indispensable to perform a task in an unstructured "hostile" environment.

In its infancy, telemanipulation technology found outstanding applications in the nuclear industry for the remote manipulation of radioactive materials in environments where human presence was hazardous [1]. Nowadays, new particularly challenging application domains are in rapid development, with medical teleoperation (telesurgery or telediagnosis) constituting one of the driving application areas. In telesurgery, particularly, the tasks to be accomplished from a distance are very complex and the role of the human operator very delicate, requiring accurate and reliable reproduction of the haptic sensations involved in carrying out such skillful operations. This general requirement is often characterized as the *transparency* of the teleoperation system, meaning the fidelity by which the human operator can perceive the remote environment, and the easiness (naturalness, intuitiveness) by which he can perform the remote task via the telerobot. In what is termed a *telehaptic* system, these feedback sensations are mediated via lightweight haptic devices (instead of larger workspace master robotic arms); these devices introduce interesting properties in the teleoperation system, notably high force-display bandwidth and eased free-space manipulation.

Nevertheless, the above mentioned requirement for transparency should not be attained at the stake of *stability*, particularly when large time delays are present in the bilateral communication and control loop. It has been recognized for many years that the presence of time delay constitutes, indeed, one of the biggest barriers in teleoperation systems. This problem is mainly due to the distance separating the master from the slave site, but may also be due to the processing time required for coding and data transmission. Such delays may be constant (e.g. in the case of direct ISDN link), but may also be varying in an unpredictable manner due to the load of the network servers (which is the case of the Internet), causing additional difficulties in coping with the problem. As a consequence, communication time delays cause certain degradation of the teleoperation system's performance; but what is even more critical, their presence may jeopardize safe operation and cause dangerous instabilities especially when force-feedback is involved in a long-distance bilateral telemanipulation system.

Time-delay has long been known in classical control theory as a very challenging problem. Classical techniques (involving in fact the reduction of feedback gains), though improving stability margins, result in a somewhat sluggish closed-loop response. To compensate this effect, predictive control schemes have been proposed based on some a-priori knowledge of the delay (for instance, the Smith predictive control, proposed around 1956; see [2] for an introduction). In the teleoperation field, some other control schemes have been proposed to cope with this problem, based on passivity theory [3], or on adaptive control [4]. All these approaches converge to the fact that, in any case, stability and transparency of the teleoperation system are two contradictory objectives, between which some kind of trade-off has to be achieved most of the times. The control system coupling the master with the slave is effectively slowed down, diminishing the control bandwidth and leading to a more compliant (less stiff) teleoperator. This ensures the stability (passivity) of the system, under some constraints related to the magnitude of the time delay, but has as a counter-effect to deteriorate transparency. The problem becomes even more difficult when time-delay is randomly varying, with no a-priori knowledge available on its order of magnitude.

To increase the control bandwidth of the system (at the master site) and, thus, ameliorate the feeling that the human operator gets when interacting with a remote environment

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by means of a teleoperator system, one solution could be to use a local approximation model of the slave-robot's environment, and control haptic interaction based on this local model. This idea, similarly to the use of predictive displays (based on virtual reality techniques) in telerobotics, could aim at 'decoupling' in fact the master from the slave, enabling the human operator to more efficiently interact with a model of the remote task. In view of the goal of *"ideal transparency"* (despite the presence of time delays in the master-slave loop) this would imply designing a model of the remote environment's impedance, and applying some type of impedance control at the master (haptic display) site. This leads to a notion of coupling the master and slave sites via some model of impedance (instead of the typical continuous force/position signal flow), which is similar to the *bilateral impedance teleoperation* architecture that has been proposed already some years ago by Hannaford [5]. Similar ideas have, more recently, been termed as *impedance reflection* teleoperation; such techniques have already been used in [6], to study friction cancellation in force-feedback telesurgery, and in [7], where a rate mode teleoperation has been applied.

The main issue, however, with this type of teleoperation control structure is to achieve fast and stable adaptation of the impedance model, in order to ensure accurate and reliable reproduction of the real environment characteristics at the haptic site. Within this context, what we propose in this paper is to apply an *adaptive impedance control* structure at the slave site, and use the on-line estimation properties of such a controller to mediate the impedance properties of the slave robot's environment ('reflecting' those back to the master site). The adaptive control law we apply in such an impedance-reflection teleoperation architecture, has already been tested before, but in a completely different context; that of a walking robot aiming to cope with environment uncertainties in legged locomotion [8]. Here, this control law is employed, though, to perform an on-line estimation of the remote impedance from real-time interaction data between the slave robot and its task environment. The structure of this control law is designed based on Lyapunov theory, to guarantee asymptotic stability. It is, indeed, considered that fast and stable convergence properties of an impedance adaptation law constitute the most crucial element in approaching an ideal teleoperation transparency.

Extensive simulations and experiments were conducted to evaluate performance in terms of transparency and stability, for which specific quantitative measures were defined. System performance is then assessed considering the presence of variable time delay, as well as of increasing environment stiffness. Comparative simulation results clearly demonstrate that the proposed controller exhibits superior performance with respect to a classical direct position-force teleoperation scheme; improved stability margin does not come at the stake of any noticeable transparency deterioration at small time delays, while for large time delays the performance gain of the proposed controller is significant. Experimental results, obtained using a Phantom Omni device as the haptic master, validate these conclusions.

This paper is organized as follows: Section II presents the theoretical aspects of the proposed teleoperation scheme, that is, the general architecture and modelling assumptions (II-A), and the design of the adaptive impedance control law (II-B). Section III then describes the simulations (III-B) and experiments (III-C) conducted to evaluate the performance of the system, and analyzes the obtained results. Concluding remarks and future work directions are given in Section IV.

II. ON-LINE IMPEDANCE ADAPTATION: THEORETICAL FORMULATION

A. Teleoperation Control Scheme - Modelling

Fig.1 shows the overall block diagram of the adaptive teleoperation scheme.

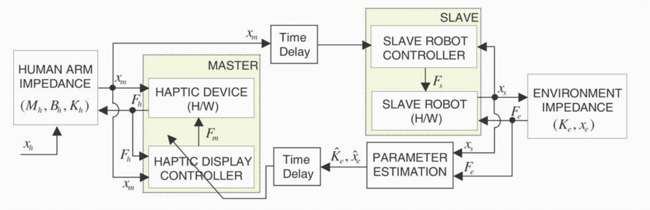


Fig. 1. *Adaptive Impedance Reflection Teleoperation Scheme*

For simulation and analysis purposes, the human arm impedance is approximately modelled as a mass-spring-damper system, described by the following linear dynamic equation:

$$M_h \cdot \ddot{X}_m + B_h \cdot \dot{X}_m + K_h \cdot (X_m - X_h) = F_h \qquad (1)$$

where F_h is the force exerted on the human hand by the haptic device, and X_h refers to the voluntary motion (desired position) issued by the human operator's sensorimotor system.

The remote (slave robot) environment is modelled by the following (static) equation:

$$F_e = K_e \cdot (x_e - x_s) \qquad (2)$$

This equation models the local impedance (better, the local stiffness) of the slave robot environment, where K_e is the stiffness, and x_e is the assumed contact (equilibrium) position for the modelled spring forces applied by the remote environment on the slave robot. x_s is the actual slave robot position. For the purposes of the analysis performed in this paper, the dynamic characteristics (inertia, friction) of the remote environment impedance are neglected, supposing relatively slow motion throughout the teleoperation task.

In direct position-force bilateral teleoperation systems, this force F_e is reflected directly on the master controller, and is displayed via the haptic interface on the human operator. However, the presence of time delays in the communication loop leads to inconsistencies in the displayed feedback forces with respect to the current master position, causing severe degradation of the teleoperation transparency, as well as system instabilities.

By applying an adaptive impedance control law, the remote environment's characteristics K_e and x_e can be estimated on-line. The estimates $\hat{K}_e$ and $\hat{x}_e$ are then "reflected" to the master system, and used to compute the forces to be displayed to the human operator. As already mentioned, the goal of such an "impedance reflection" teleoperation system is in fact to decouple, in a way, the master and slave systems, letting the human operator haptically interact with a locally emulated (but continuously adapted) model of the remote environment impedance. The stability of the interaction in the presence of time delays now depends on the stability properties of the impedance adaptation law. The challenge is, of course, to ensure the quality of the system's transparency, from the human operator's perspective, that is, the matching between the impedance perceived by the human operator and the real remote environment characteristics. The goal of this paper is to design such an impedance adaptation law, and analyze its performance in terms of transparency and stability, particularly in relation to the round-trip time delay in the teleoperation loop.

B. Impedance Adaptation

As described above in equation (2), we assume that the slave robot is in contact interacting with an environment modelled simply as a surface with stiffness coefficient K_e and apparent equilibrium position of the spring-like forces at position x_e. The impedance characteristics, K_e and x_e, of the remote environment are of course unknown within the master system. The forces applied to the human operator by the haptic display controller are, thus, computed using estimated impedance values, $\hat{K}_e$ and $\hat{x}_e$, as follows:

$$F_m = \hat{K}_e \cdot (\hat{x}_e - x_m) \tag{3}$$

As already described the goal is to give to the human operator an accurate impression about interacting (stably) with a "virtual impedance" that matches as closely as possible the real remote environment impedance. For this purpose, we design an adaptive impedance control law that provides an on-line estimate of the actual remote impedance characteristics K_e, x_e, where the goal is to minimize the *force estimation error*, defined as:

$$e_f = \hat{F}_e - F_e \tag{4}$$

$\hat{F}_e$ defines the *estimated reaction force*:

$$\hat{F}_e = \hat{K}_e \cdot (\hat{x}_e - x_s) \tag{5}$$

The first step in designing an adaptation law is to define a linear parameterization of the system equation. K_e and x_e are, in our case, the impedance parameters to be estimated on-line. Let us, thus, define the impedance parameter vector as:

$$\theta_e = [K_e,\ F_0]^T \tag{6}$$

where $F_0 = K_e \cdot x_e$. The estimated reaction force in equation (5) can be then written as:

$$\hat{F}_e = \hat{K}_e \cdot \hat{x}_e - \hat{K}_e \cdot x_s = [-x_s\ ,\ 1] \cdot \hat{\theta}_e \tag{7}$$

where $\hat{\theta}_e$ defines the *impedance parameter vector estimate*:

$$\hat{\theta}_e = [\hat{K}_e,\ \hat{F}_0]^T = [\hat{K}_e,\ \hat{K}_e \cdot \hat{x}_e]^T \tag{8}$$

The force estimation error in equation (4) then becomes:

$$e_f = \hat{F}_e - F_e = [-x_s\ ,\ 1] \cdot \tilde{\theta}_e \tag{9}$$

where the $\tilde{\theta}_e$ defines the *impedance parameter estimation error*:

$$\tilde{\theta}_e = \hat{\theta}_e - \theta_e = \begin{bmatrix} \hat{K}_e - K_e \\ \hat{F}_0 - F_0 \end{bmatrix} \tag{10}$$

Let us now assume a general adaptation law:

$$\dot{\hat{\theta}}_e = -\gamma_\theta \cdot e_f \overset{(4)}{=} -\gamma_\theta \cdot (\hat{F}_e - F_e) \tag{11}$$

where $\gamma_\theta = [\gamma_{\theta 1},\ \gamma_{\theta 2}]^T$ is a vector containing adaptation gains, and e_f is assumed as the observation (output error) signal, that is, the force estimation error between estimated and actual measured force applied at the slave robot, defined as in equations (4) and (9). To study the asymptotic stability of the system, let us now define a Lyapunov candidate function as a quadratic function of the parameter estimation error:

$$V_e = \frac{1}{2} \cdot \tilde{\theta}_e^T \cdot \Gamma_e \cdot \tilde{\theta}_e \tag{12}$$

where Γ_e is chosen as a symmetric, positive-definite (2x2) matrix. Differentiating (12) we then get:

$$\dot{V}_e = \tilde{\theta}_e^T \cdot \Gamma_e \cdot \dot{\tilde{\theta}}_e \tag{13}$$

Assuming now that θ_e is constant, equation (10), defining the impedance parameter estimation error, gives:

$$\dot{\tilde{\theta}}_e = \dot{\hat{\theta}}_e - \dot{\theta}_e = \dot{\hat{\theta}}_e \tag{14}$$

and equation (13) then becomes:

$$\dot{V}_e = \tilde{\theta}_e^T \cdot \Gamma_e \cdot \dot{\hat{\theta}}_e \tag{15}$$

Introducing in the above equation the adaptation law from (11) we obtain:

$$\dot{V}_e = -\tilde{\theta}_e^T \cdot \Gamma_e \cdot \gamma_\theta \cdot (\hat{F}_e - F_e) \tag{16}$$

The problem now becomes that of designing the adaptation gains in γ_θ such that the derivative of the Lyapunov function remains negative at all times. By thus defining:

$$\gamma_\theta = \Gamma_e^{-1} \cdot \begin{bmatrix} -x_s \\ 1 \end{bmatrix} \tag{17}$$

equation (16) becomes:

$$\dot{V}_e = -\tilde{\theta}_e^T \cdot \begin{bmatrix} -x_s \\ 1 \end{bmatrix} \cdot (\hat{F}_e - F_e) \tag{18}$$

from where by substituting equation (9) we finally get:

$$\dot{V}_e = -(\hat{F}_e - F_e)^2 < 0 \tag{19}$$

Asymptotic stability is, thus, guaranteed, if the adaptation gains are designed as in (17).

From equation (8) we have:

$$\dot{\hat{\theta}}_e = \left[\begin{array}{c} \dot{\hat{K}}_e \\ \dot{\hat{F}}_0 \end{array} \right] = \left[\begin{array}{c} \dot{\hat{K}}_e \\ \dot{\hat{K}}_e \cdot \hat{x}_e + \hat{K}_e \cdot \dot{\hat{x}}_e \end{array} \right] \qquad (20)$$

If we take Γ_e to be diagonal:

$$\Gamma_e = \mathrm{diag}[\gamma'_{ei}]_{(i=1,2)} \quad (\text{with } \gamma'_{ei} > 0)$$

and define the adaptation gains in Γ_e^{-1} as:

$$\Gamma_e^{-1} = \mathrm{diag}[\gamma_{ei}]_{(i=1,2)} \quad (\text{where } \gamma_{ei} = (1/\gamma'_{ei}) > 0)$$

the adaptation law for the impedance parameters (K_e, x_e) can then be written, by combining equations (11), (17) and (20), as:

$$\left[\begin{array}{c} \dot{\hat{K}}_e \\ \dot{\hat{K}}_e \cdot \hat{x}_e + \hat{K}_e \cdot \dot{\hat{x}}_e \end{array} \right] = - \left[\begin{array}{cc} \gamma_{e1} & 0 \\ 0 & \gamma_{e2} \end{array} \right] \cdot \left[\begin{array}{c} -x_s \\ 1 \end{array} \right] \cdot e_f \qquad (21)$$

from where we finally get:

$$\dot{\hat{K}}_e = \gamma_{e1} \cdot x_s \cdot (\hat{F}_e - F_e) \qquad (22)$$

and

$$\dot{\hat{x}}_e = \frac{(\hat{F}_e - F_e)}{\hat{K}_e} \cdot (-\gamma_{e2} - \gamma_{e1} \cdot x_s \cdot \hat{x}_e) \qquad (23)$$

Equations (22) and (23) are used to compute on-line updates for the estimates of the (slave robot's environment) impedance parameters ($\hat{K}_e$ and $\hat{x}_e$). These estimates are then 'reflected' back to the haptic display controller at the master site, as shown in Fig. 1, and constitute the local impedance model used to compute the forces applied to the human operator according to equation (3).

III. EXPERIMENTS

To validate the proposed adaptive impedance teleoperation control scheme presented in the previous section, and to assess its performance with respect to an increasing time delay, we used two experimental evaluation approaches: (a) firstly, we performed a series of simulations, assuming a linear motion of the master-haptic interface, with a linearized model for the human-arm impedance, and (b) we performed actual experiments, using a real haptic (desktop force-feedback) device to couple the human operator with the slave system. In both cases, the hypothetical slave system consisted of a simulated (single axis) robot with a linear stiffness as the task environment, while a variable time delay was emulated using a buffering algorithm.

A. Experimental Setup

The overall experimental system that we used to test the adaptive impedance teleoperation scheme comprises the following four main components (Fig. 2):

- Haptic Interface Device: A Phantom Omni device was used at the master interface in the real experiments case. This device captures motion (position and orientation in three dimensions) of the human hand manipulating the handle and displays forces in three axes. The device communicates with the master computer via a USB port.

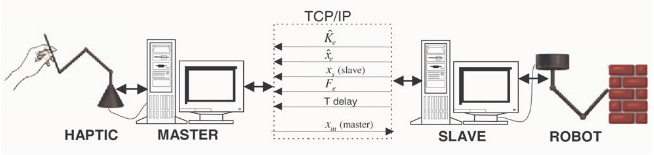


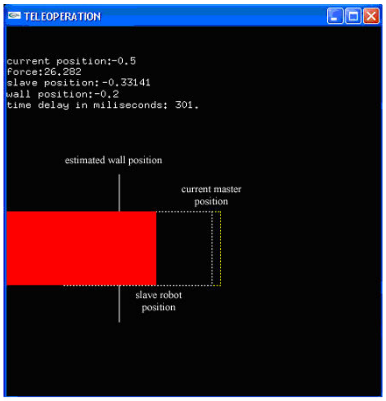
Fig. 2. *Overall Experimental Setup: Hardware Configuration*

- Master Controller Computer: It performs all operations related to the computation of feedback forces based on the local (adaptive) impedance model, communication and control of the haptic interaction device, as well as communication via the network with the remote (slave) system.
- Slave Controller Computer: This is a remote computer in charge of controlling the slave robot. It receives command signals from the master station, and reflects feedback information, which includes updating the estimated impedance parameters as described in the previous section.
- Slave Robot: In this experimental series we will not use a real slave robotic device but, instead, a simulated slave site consisting of a single (linear) axis robot in potential contact with a virtual wall (of linear stiffness K_e and at position x_e).

1) Master-Slave Communication and Time Delay: The master and slave computers are connected via a local area network, exchanging data on a shared port (via tcp/ip sockets). The master computer operates as the server station waiting for a connection from a remote client, the slave computer. When the two computers are connected, they read/write data streams on the shared port. The data that the master computer transmits is, in our case, simply the current position x_m of the haptic device (simulated or real). Accordingly, the data that are sent back by the slave consist of: (i) the force F_e experienced by the slave robot, (ii) the current position x_s of the (in our case, simulated) slave robot, (iii) the estimated impedance parameters ($\hat{K}_e$, $\hat{x}_e$) of the slave environment (in this case, a virtual wall).

Physical connection between the master and slave computers is performed via a local area network, which introduces a very small latency in the communication. To introduce and emulate a variable time delay in the master-slave communication loop, we use a buffering algorithm. Data are temporarily stored in a buffer (that functions, in fact, like a queue) before actually being processed; the size of the buffer depends on the master and slave controllers sampling frequencies and the assumed communication latency.

2) Master Control Interface: A simple graphical user interface is used at the master computer, visualizing the current haptic device position x_m as well as the currently reflected position of the slave robot. The currently estimated position $\hat{x}_e$ of the remote environment (virtual wall) is also visualized. Figure 3 shows a snapshot of the master graphical user interface. Graphic display is done using simple (2D) OpenGL commands, and is meant to give the user a visual impression of the communication and control latency, as well as of the adaptive impedance operation (meaning, the progressive online estimation and updating of the remote virtual wall impedance parameters).



```
current position:-0.5
force:26.282
slave position:-0.33141
wall position:-0.2
time delay in miliseconds: 301.
```

Fig. 3. *Snapshot of the master graphical user interface*

B. Simulation Results

At the first series of experiments we did not use a real haptic device at the master site; instead, we emulated a hypothetical motion of the haptic handle, coupled with a linear human-arm impedance, of the form of equation (1), and linked via the tcp/ip channel with the simulated slave robot and virtual environment. The emulated motion at the haptic interface consists of a linear, constant velocity movement (illustrated in Fig. 5), representing in fact the intended (reference) motion of the human arm manipulating the haptic handle (referred to as x_h in the haptic teleoperation model of Fig. 1). The parameters of the human arm impedance model, for the simulation series, were set as: $M_h = 1$Kg, $B_h = 20$Nt.s/m and $K_h = 160$Nt/m (these values correspond, as far as the simulated dynamics of the human arm are concerned, to a time constant of approximately 0.1 sec and a damping coefficient $\zeta \simeq 0.8$). In the rest of this section, we assume that a virtual wall is placed at the (linear) workspace of the (simulated, single axis) slave robot, at position $x_e = -0.2\,\text{m}$, with stiffness (where not mentioned) $K_e = 200\,\text{Nt/m}$.

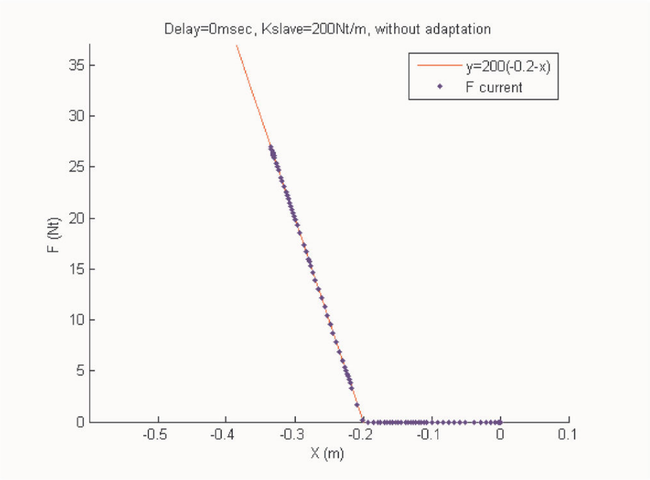


Fig. 4. *Simulated master force F_m, with respect to the ideal environment impedance (linear stiffness), with zero delay and no impedance adaptation*

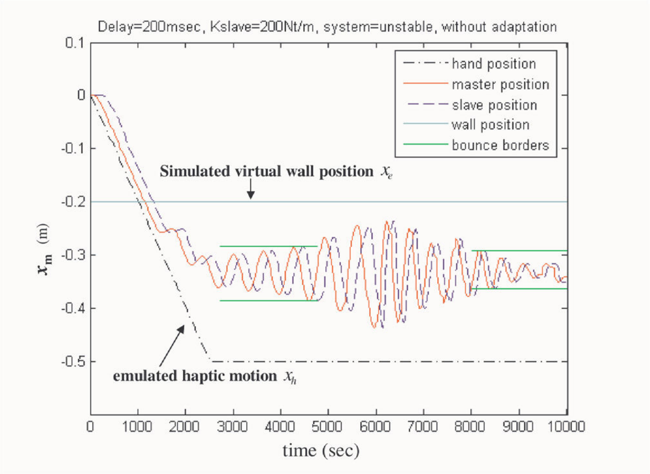


Fig. 5. *Simulated master and slave positions, with time delay = 200 msecs (and without impedance adaptation)*

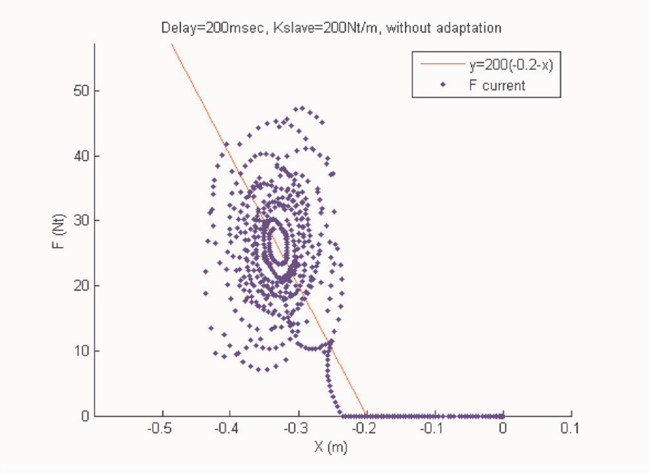


Fig. 6. *Simulated master force, with time delay = 200 msecs (and without impedance adaptation)*

1) Without Impedance Adaptation: We firstly assume that there is no communication latency between the master and slave stations. If we employ a direct position-force teleoperation scheme (without any impedance adaptation) the simulation results we obtain correspond, as could be expected, to an ideal response, which is depicted in Fig. 4, demonstrating a perfect transparency. On the contrary, if we assume a round-trip delay of 200 msecs, then the respective results we obtain are shown in figures 5 and 6. It is evident from these results that the presence of even a small time delay may destabilize a classical direct (position-force) teleoperator, deteriorating significantly the human-operator's local perception of the remote environment (as is shown by the "hysteresis" like graph of Fig. 6).

2) Performance - Transparency and Stability: Let us now try to quantify the performance of the system, by defining a measure of transparency, meaning: how close the matching is between what the human operator locally perceives and what the impedance properties of the remote environment

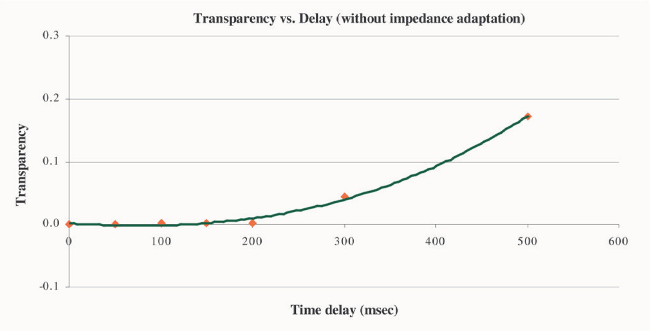


Fig. 7. *Transparency degradation with increasing time delay (without impedance adaptation)*

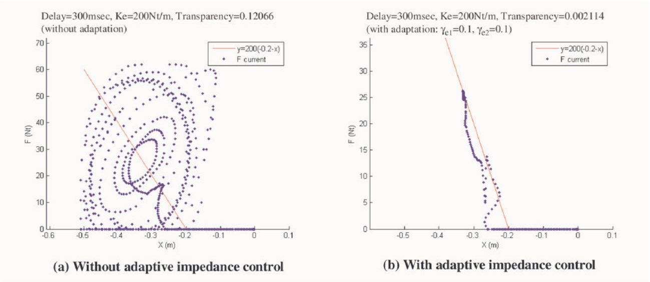
actually are. In our case, the remote (slave robot) environment corresponds to a virtual wall with linear stiffness that can be described by the ideal equation (at the *X*-*F* plane): $F = -200X - 40$. To obtain a measure of transparency of the tele-haptic system, we can compute the distance of all (x_m, F_m) points (with $x_m < x_e$) from the above line equation (which represents the ideal linear stiffness). The distance of any point $(x_m^{(i)}, F_m^{(i)})$ $(i = 1, \ldots, N)$ from line: $A \cdot X + B \cdot F + C = 0$ (in our case, $A = 200$, $B = 1$, $C = 40$, and $x_e = -0.2$) is given by:

$$d_i = \left| \frac{x_m^{(i)} \cdot A + F_m^{(i)} \cdot B + C}{\sqrt{A^2 + B^2}} \right| \tag{24}$$

The sum of the distances of all these points from the ideal line, divided by the number (N) of measurement points, can indeed constitute an objective measure of transparency, in this linear stiffness case:

$$\text{Transparency} = \frac{1}{N} \cdot \sum_{i=1}^{N} d_i \tag{25}$$

Applying this formula for various time delay values, we obtain the results depicted in Fig. 7 (where also a polynomial interpolation is plotted of the Transparency values vs. Time delay). From this plot we can indeed observe a clear transparency degradation- increased measure of transparency, as defined in Eq. (25)- when the time delay rises from 0 to 500 msecs. This means that, as communication latency increases, the human operator gets an increasingly wrong perception of the remote environment's impedance, which is indeed known to constitute one of the biggest performance barriers in force-feedback teleoperation.



(a) Without adaptive impedance control

(b) With adaptive impedance control

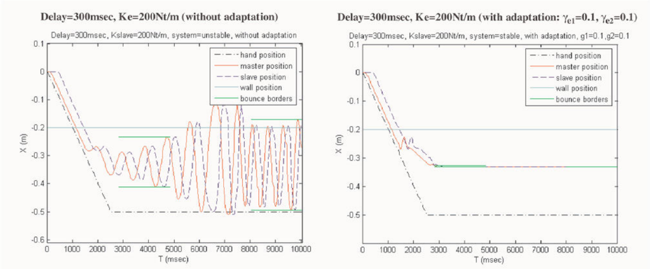
Fig. 8. *Simulated master force with respect to the ideal transparency (linear stiffness): (a) without, and (b) with adaptive impedance teleoperation control*

Regarding stability, we also need to define an objective measure that can be easily computed by the observed data. In assessing stability, we consider the capacity of the system (in this case the simulated haptic device motion) to settle as quickly as possible to a steady state, after the introduction of an external disturbance, in this case after contact of the remote simulated slave robot with the virtual environment. For the experiments conducted in this study, we defined a measure of stability as follows: we record the master positions for an interval comprising the first 2 secs after initial application of a feedback force $F_m > 0$, and compute the sum of squared distances (SSD_1) of these recorded positions from their mean value (settling point). This is compared to the SSD value (SSD_2) obtained for the last two seconds of motion (in our case, seconds 8 to 10 of simulated motion). If $\text{SSD}_2 < \lambda{\cdot}\text{SSD}_1$ $(\lambda \in (0, 1))$, then the system can be considered to exhibit some asymptotic stability properties (oscillatory response pattern progressively vanishes out to a settling point), and the system is characterized as stable (in our case we chose $\lambda = 1/2$); otherwise, the system is considered to be unstable, due to persistent oscillations in the observed output. This is illustrated in Fig. 5, where the horizontal (green) lines for the first and last two seconds of motion (after initial contact with the environment) delimit the max and min values of the resulting master (simulated haptic interface) positions.

A series of experiments were conducted for increasing stiffness value K_e and for various time delay values. For each value of the time delay, a critical stiffness K_c was identified, which corresponds to the maximum value of the environment stiffness below which the system response remains stable (that is, for $K_e > K_c$ the system becomes unstable). Comparative simulation results (with vs. without the application of adaptive impedance control) in terms of stability are presented in the following paragraph.

3) With Adaptive Impedance Control: In this paragraph we apply the adaptive impedance teleoperation scheme proposed in section II-B, with $\gamma_{e1} = 0.1$ and $\gamma_{e2} = 0.1$. We assume again a simulated intended haptic motion as before, and a simulated slave robot with a virtual wall as the remote environment (with $x_e = -0.2m$ at the slave site). Fig. 8 shows the comparative (with vs. without adaptive impedance teleoperation control) results we obtain for the simulated master force, illustrating performance with respect to the ideal transparency (with delay = 300 msecs). A sample of the results we obtain regarding system stability is shown in Fig. 9, where we can observe again the significant comparative performance amelioration when the proposed adaptive impedance teleoperation scheme is applied.

The overall comparative results we obtain for transparency and stability are shown in Figures 10 and 11, respectively. A global conclusion that can be drawn from these graphs is that the teleoperation stability margin increases significantly when the adaptive impedance teleoperation control scheme is applied. We can observe, though, that within the stability



(a) Without adaptive impedance control **(b) With adaptive impedance control**

Fig. 9. *Simulated master position response, illustrating system stability: (a) without, and (b) with adaptive impedance teleoperation control*

margin, the two controllers (direct position-force teleoperation vs. adaptive impedance reflection teleoperation) perform similarly, with a very slight performance improvement (in terms of perceived transparency) for the direct teleoperation case. This can also be concluded by analyzing the results shown in Table I, presenting the values of Transparency for various time delays, comparatively, with vs. without adaptive impedance control. However, even a small time delay (300msecs or more, for $K_e = 200$ Nt/m) quickly destabilizes the direct teleoperation system (without impedance adaptation case) leading to a significant deterioration of system performance, in terms of transparency, demonstrating the superior performance of the adaptive impedance scheme, as is clearly depicted in Figures 10 and 11.

TABLE I

COMPARATIVE SIMULATION RESULTS FOR TRANSPARENCY (WITHOUT VS. WITH IMPEDANCE ADAPTATION)

	Transparency	
Delay (msec)	without	with
0	0.0000000	0.0000000
50	0.0010490	0.0011532
100	0.0021698	0.0012505
150	0.0024793	0.0017616
200	0.0029421	0.0034311
300	0.0434010	0.0197600
500	0.1720800	0.0219120

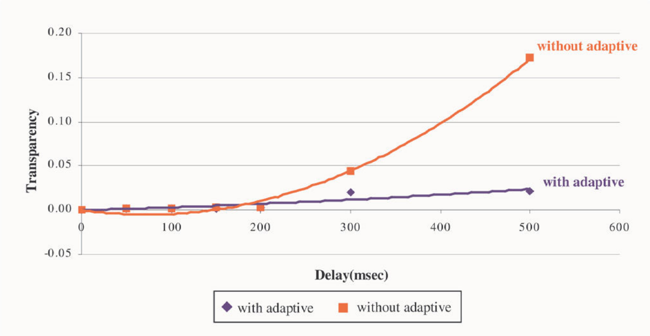


Fig. 10. *Comparative results for Transparency (with vs. without adaptive impedance teleoperation control) with increasing time delay (for $K_e = 200$)*

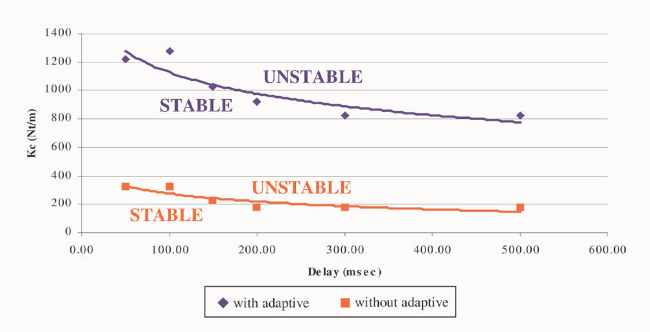


Fig. 11. *Comparative results for Stability (critical stiffness, with vs. without adaptive impedance teleoperation control) with increasing time delay*

C. *Experimental Results*

We have used a real haptic (force feedback) device to experimentally validate the conclusions drawn from the simulation results presented in the previous section. Instead of the simulated reference motion of the haptic interface at the master site, a Phantom Omni device was interfaced with the master control computer. The slave site remained unchanged, consisting of a simulated single-axis robot with a linear stiffness (virtual wall) as the simulated remote environment.

We performed a set of experimental sessions, each one consisting of a series of ten (10) trials. In each trial, the human operator (user) was asked to perform a specified task that consisted of moving the haptic handle towards a specific direction, with the goal being to control the (simulated) slave robot to enter in contact with the virtual surface at the remote site. The instructions given to the human operator were to follow a prescribed, constant velocity, linear motion "in search" of the virtual surface, and to try to control the level of the force F_e, applied at the remote (slave) site, between prespecified bounds for at least 4 secs (in this case, we chose: $1.26\text{N} < F_e < 1,54\text{N}$). A trial was considered successful when this was achieved, and the task completion time for each trial was recorded. We also recorded the force error (deviation of F_e from the desired force level of 1.4 N). The time limit for successful completion of each trial was set to 10 secs, beyond which the task was considered as failed.

Within each experimental session, the position of the virtual wall changed randomly between the individual trials, in order to eliminate any memorization effect from the user. Furthermore, the choice of the control scheme (application or not of the adaptive impedance controller) varied in a random way, so that the human operator had no a-priori knowledge of the scheme that was applied in each experimental trial.

Figures 12 and 13 depict the results we obtained regarding the mean trial completion time and mean force error (for variable time delay increasing from 50 msecs to 2 secs), comparatively for the two experimental conditions (that is, with and without the application of the adaptive impedance control scheme). The superior performance of the adaptive impedance teleoperation scheme is evident in both graphs, particularly when the time delay exceeds a threshold value (in this experiment, this value was found to be approximately

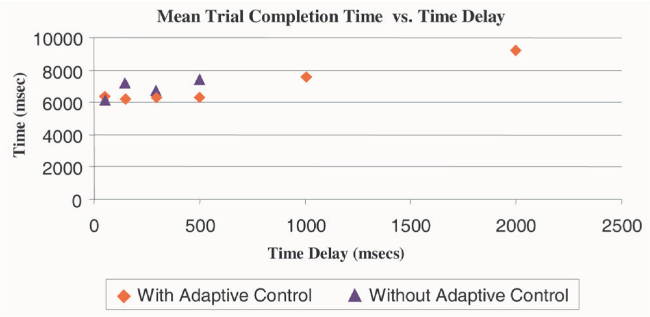


Fig. 12. *Experimental Results: Mean completion time vs. time delay.*

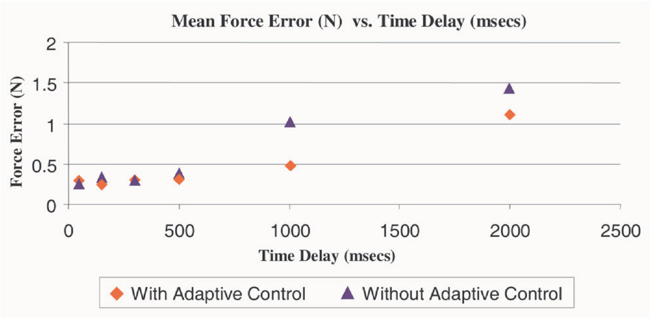


Fig. 13. *Experimental Results: Mean force error with increasing delay.*

half a second). It is worth noting that, when the classical direct (position-force) teleoperation scheme was applied (i.e. without adaptive impedance control), and the time delay was 1 sec or above, the users were unable to successfully complete any of the trials (that is, control the applied force within the specified error bounds and time limits); this explains the absence of relative data (mean trial completion time without adaptive control) in Fig. 12, for the Time Delay values of 1 and 2 secs.

IV. CONCLUSION AND FUTURE WORK

In this paper we proposed a new haptic teleoperation scheme, using an adaptive impedance control law within a general impedance-reflection architecture. The main issue in such teleoperation schemes is to achieve fast and stable impedance adaptation, in order to ensure accurate and reliable reproduction of the real environment characteristics at the haptic site. The structure of the proposed impedance adaptation law is designed to guarantee Lyapunov stability. Indeed, fast and stable convergence of the impedance adaptation law is considered, here, as the most crucial part in approaching an ideal transparency performance, when interacting with an unknown environment.

Quantitative performance measures are defined to evaluate the teleoperator's transparency and stability. Performance is assessed considering the presence of variable time delay and increasing environment stiffness. Extensive comparative simulation results demonstrate that the proposed controller has superior performance, with respect to a classical direct position-force teleoperation scheme; improved stability margin does not come at the stake of any noticeable transparency degradation for small time delays, while for large time delays the performance gain of the proposed controller is significant. Experimental results, obtained using a Phantom Omni device as the haptic master, validate these conclusions.

Future work will aim at a twofold direction: (a) to generalize the structure of the adaptive impedance controller to cope with (i) more degrees of freedom, (ii) dynamic impedance characteristics, as well as (iii) time and space varying environment properties; and (b) to conduct experimental (psychophysical) evaluation studies, assessing human *telehaptic perception* performance, with respect to various mechanical impedance properties (e.g. evaluation of stiffness perception thresholds).

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