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Telehaptic Perception of Delayed Stiffness Using Adaptive Impedance Control: Experimental Psychophysical Analysis

Abstract

Telehaptics is the science of transmitting touch-related sensations over computer networks. With respect to robot teleoperation, telehaptics emphasizes more on reliably reproducing physical properties of a remote environment, as mediated over a network through the use of appropriate haptic interfacing technologies. One of the main factors that can cause degradation of the quality of a telehaptic system is the presence of time delays. Inspired by concepts such as impedance-reflection and model-mediated telemanipulation, an adaptive impedance control scheme has been proposed aiming to mitigate some of the problems caused by network delays in a telehaptic system. This paper presents an experimental analysis, which has been conducted to assess the actual performance of the proposed telehaptic scheme in terms of both control and human perception objectives. Firstly, a set of comparative numerical experiments is presented aiming to analyze stability and characterize transparency of the telehaptic system under large time delays. The results show the superior performance of the proposed adaptive impedance scheme as compared to direct force-reflecting teleoperation. Then, a series of psychophysical experiments is described, to evaluate the performance of the telehaptic system with respect to human perception of remote (delayed) stiffness. An analysis of the obtained results shows that the proposed adaptive scheme significantly improves telehaptic perception of linear stiffness in the presence of network delays, maintaining perceptual thresholds close to the ones obtained in the case of direct, nondelayed stimuli. A comparative experimental evaluation of psychometric transparency confirms the superior robustness with regard to time delay of the adaptive impedance telehaptic scheme as compared to state-of-the-art position/force transparentizing methods.

1 Introduction

Telehaptics refers to the scientific and technological field concerning the transmission of touch-related sensations (i.e., perceiving tangible physical characteristics) over computer networks. The goal of telehaptic systems is, thus, to bring the sense of touch over network connections (Shen & Shirmohammadi, 2006). This may involve one human interacting with one machine (robot) over a network, but may also refer to multiple humans remotely interacting with each other and with multiple machines over a network, by means of specialized

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sensors and effectors. Naturally, telehaptic interaction is intrinsically bilateral and involves both: (1) issuing (mainly manual) actions, and (2) tele-perceiving (principally tangible) physical properties of the distant environment.

Bilateral control over a network is a subject largely studied in the field of robot teleoperation, involving all the methodologies and technologies that enable a human operator to perform a task from a distance through the use of intermediate mechatronic (robotic) systems. Telehaptics can thus be seen as a scientific domain emerging at the crossroads of telerobotics (Sheridan, 1992) and virtual reality (Burdea & Coiffet, 2003), exploiting synergies of theories and technologies emanating particularly from the fields of haptic display (Burdea, 1996) and robot telemanipulation. In its infancy, telemanipulation technology found outstanding applications in environments where human presence was hazardous (Vertut & Coiffet, 1985). 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 in the current literature as the *transparency* of the teleoperation system, meaning the fidelity by which the human operator can "feel" the remote environment, which also provides a measure of how well he or she can control the remote system and perform the remote task via the telerobot (Slawiñski & Mut, 2008).

In telehaptic systems, 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. Therefore, telehaptics is emphasizing more on the creation of artificial touch sensations, accurately and realistically reproducing physical properties of a remote environment, as mediated through the use of appropriate robotic and haptic interfacing technologies. In this paper, the emphasis is put on telehaptic perception of specific kinesthetic features. Such physical properties may include the perception of force, weight, stiffness, friction, damping, and inertia (mass), as well as more general shape features involved in kinesthetic exploration of an object, such as curvature, among others. The results presented in this paper focus on the perception of stiffness and demonstrate the performance that can be achieved in a telehaptic experimental setup.

Of course, as in any feedback control system, closed-loop stability in bilateral teleoperation is also a major issue. This means that the above-mentioned requirement for transparency and feedback fidelity should not be attained at the stake of *stability*. This requirement becomes particularly challenging 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, but may also vary in an unpredictable manner, for instance, due to the load of network servers, causing additional difficulties to cope with the problem. As a consequence, communication delays cause degradation of teleoperation performance, and may jeopardize stable and safe operation, especially when force-feedback is involved in long-distance telemanipulation.

1.1 Time Delay in Teleoperation Control Systems

Time delay has long been known in classical control theory as a very challenging problem. Classical techniques (involving the reduction of feedback gains), though they improve stability margins, result in a somewhat sluggish closed-loop response. To compensate for this effect, predictive control schemes have been proposed based on some a priori knowledge of the delay (i.e., the Smith predictive control; see Wang, Liu, Harris, & Brown, 1995, for an introduction). In teleoperation, several other control schemes have been proposed to cope with this problem, based, for instance, on passivity theory (Anderson & Spong, 1992), or on adaptive control (Niemeyer & Slotine, 1991). 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. 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 the countereffect of deteriorating 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, to ameliorate the feeling that the human operator gets when interacting with a remote environment by means of a teleoperator, one solution could be to use a local approximation model of the slave-robot's environment and to control haptic interaction based on this model. This idea, similar to the use of predictive displays (based on virtual reality techniques) in telerobotics, aims to decouple, in a sense, the master from the slave, enabling the human operator to interact with a local model of the remote task. In view of our goal for ideal transparency (despite the presence of time delays in the master–slave loop), this idea implies designing a model of the remote environment's impedance and applying some type of impedance control at the haptic master site. This leads to a concept 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 idea of bilateral impedance teleoperation architecture originally proposed some years ago by Hannaford (1989).

1.2 Model-Mediated and Impedance-Reflection Telemanipulation

More recently, similar concepts to the one proposed in Hannaford (1989) have been developed using terms such as impedance reflection (Hashtrudi-Zaad & Salcudean, 1996) or, more generally, model-mediated teleoperation (Mitra & Niemeyer, 2008). Initial work, reported in Hashtrudi-Zaad and Salcudean, proposed an impedance reflection scheme, employing an adaptive control method that does not require direct force sensing. Numerical simulations were presented to test force tracking and stability with time delays of up to 300 ms, but no experiments were reported at the time. In more recent work, Mobasser and Hashtrudi-Zaad (2007) applied an impedance-reflecting force-position control architecture, using a laser proximity sensor to predict the collision time between the slave and its environment, which was verified experimentally on a 1-DOF setup with communication delays of up to 200 ms. A shaped stiffness reflection controller was presented in Willaert, Goethals, Reynaerts, Van Brussel, and Vander Poorten (2010), aiming to enhance perceptual sensitivity with the focus on telesurgery applications; whereas a relevant adaptive stiffness reflection strategy was proposed in Willaert, Vander Poorten, Reynaerts, and Van Brussel (2008), where a switching strategy was applied between soft tissue rendering and hard contact display. Similar impedance reflection techniques were also used in Goethals, De Gersem, Sette, Reynaerts, and Van Brussel (2007), to study friction cancellation in force-feedback telesurgery, and in Mobasser, Hashtrudi-Zaad, and Salcudean (2003), where a rate mode teleoperation was applied. A relevant adaptive impedance control strategy was proposed in Love and Book (2004), where the estimated stiffness of the slave environment was used to continuously adapt the damping of the master control loop. Experiments were conducted to assess performance in terms of stability and human applied energy, using a large-scale slave robot manipulator, but without considering network delays. Chang and Okamura (2004) also proposed an impedance-reflecting architecture, which uses a real-time evolving neural network controller for parameter estimation, but also without considering time delays in the experimental validation.

Relevant ideas have been described by Mitra and Niemeyer (2008), who proposed the more general concept of model-mediated telemanipulation, inspired by relevant work in the field of telerobotics. It is argued in Mitra and Niemeyer (2008) that for successful teleoperation, the level of network delay must be matched by a level of abstraction in the communication. The concept was demonstrated on a 1-DOF telemanipulation setup, which involved detecting and haptically displaying a single rigid contact. Relevant work has been presented in Mitra, Gentry, and Niemeyer (2007), where various transition interfaces were examined, to mitigate the effects of abrupt model updates from a user preference perspective. An extension of this concept to multi-user systems has also been proposed in Passenberg, Peer, and Buss (2010), where an algorithm to estimate the mass of a manipulated object was used and experimentally validated on a 1-DOF setup. All the above works apply variations of recursive least-square (RLS) techniques to perform online parameter estimation. Kalman filtering techniques are also sometimes used, like in the work of Willaert et al. (2010), or using Kalman active observers as proposed in Cortesao, Park, and Khatib (2006). These techniques are able to effectively differentiate soft and stiff objects, but require a number of parameters to be carefully tuned in advance.

Inspired by these concepts and the related literature outlined above, in this paper we apply a different approach based on the estimation properties of an adaptive controller. The main issue in this type of teleoperation architecture is to achieve fast and stable adaptation of the slave environment model, in order to ensure reliable reproduction of its physical characteristics at the master haptic site. Within this context, we apply an adaptive impedance control structure at the slave site and use the online estimation properties of such a controller to mediate the impedance characteristics of the slave robot's environment, reflecting those back to the master site. This approach differs from previous work involving other estimation schemes (i.e., RLS-based estimation) in that the parameter update law is derived based on adaptive control design principles, providing some theoretical and practical advantages, namely, a flexible and integrated framework for stability analysis and for control implementation. In particular: (1) the stability of the closed-loop system can be analyzed using Lyapunov theory and the adaptation law can be designed accordingly to guarantee stability; (2) telehaptic display can be an integral part of a full-scale adaptive dynamic impedance controller, where adaptation could also concern other dynamic parameters of the whole closed-loop system for which some uncertainty may exist (e.g., human and robot dynamic parameters). The estimated (slave environment impedance) parameters can then be directly involved in the master haptic display controller, affecting position control setpoints and online regulation of the feedback gains.

Stability analysis and control design of such an adaptive impedance control law has been addressed in previous work (Tzafestas, M'Sirdi, & Manamani, 1997), where such a controller (involving dynamic parameter estimation integrated for both the robot and its environment) has been implemented in a completely different context, that of a walking robot aiming to cope with environment uncertainties during legged locomotion. The application of such a controller in robot teleoperation was initially proposed in previous work by Tzafestas, Velanas and Fakiridis (2008), where stability analysis was performed and low-level control performance (in terms of fast convergence rates) was demonstrated. The main goal of the work presented in this paper is to adapt this control scheme in a model-mediated telehaptic exploration context, and to assess its applicability in such a context by conducting an experimental analysis, aiming, in particular, to evaluate the performance achieved in terms of telehaptic perception and transparency. Extensive numerical experiments have been conducted to evaluate performance in terms of the tradeoff achieved between transparency and stability, considering the presence of variable time delay and increasing environment stiffness. The results presented in this paper demonstrate that the adaptive impedance scheme exhibits superior performance compared to direct force-reflecting teleoperation; improved stability margin does not come at the expense of transparency for small time delays, while for large time delays the performance gain obtained by the proposed controller is significant. Experimental results, obtained using a PHANToM Omni device as the haptic master, also validate these conclusions.

1.3 Haptic Perception of Delayed Stiffness

To further assess the performance of the proposed telehaptic control system, this paper describes a series of psychophysical experiments, which have been performed to study human haptic perception of real remote (delayed or nondelayed) stiffness, by employing the experimental setup reported in Velanas and Tzafestas (2010). In this experimental analysis, instead of using a virtual (simulated) slave site, the haptic master is now coupled (via a computer network) to another haptic device (a PHANToM desktop device), used as a slave robot that physically interacts, this time, with a real environment consisting of a set of linear springs.

In a number of recent studies, the effect of delay in the perception of virtual stiffness has been assessed in terms of the PSE (Point of Subjective Equality) values (Pressman, Nisky, Karniel, & Mussa-Ivaldi, 2008), as well as by examining variations of the Just Noticeable Difference (JND), as in the work of Nisky, Mussa-Ivaldi, and Karniel (2008). In this paper, we present two experimental studies that assess human telehaptic perceptual performance under time delay. Firstly, discrimination of delayed stiffness fields is assessed in terms of JND values, using a forced-choice psychophysical protocol. In this experiment, the human operator manipulates the haptic master and telehaptically explores the kinesthetic properties (stiffness) of a real remote physical environment (in this case, consisting of probing a set of remote linear springs). An analysis of the obtained experimental results shows that, when using the adaptive impedance telehaptic controller, the effect of time delay in perception is compensated for, meaning that the quality of the haptic sensations induced at the master site is significantly ameliorated despite the presence of a significant delay in the loop. As will be demonstrated in this paper, the proposed adaptive impedance control scheme appears to maintain the threshold of human haptic perception close to the values obtained in the case of direct, nondelayed stimuli.

A second experimental study is also presented in this paper, aiming to further assess the kinesthetic performance of the proposed telehaptic control scheme in comparison to state-of-the-art approaches for transparent teleoperation under time delay. In particular, a comparative experimental analysis is conducted, evaluating the proposed adaptive control scheme in comparison to a so-called transparentizing method proposed recently in Nisky, Pressman, Pugh, Mussa-lvaldi, and Karniel (2011). The experimental analysis focuses on comparatively evaluating psychometric transparency, by measuring this time the differences in PSE values under different time delay conditions and choices for the control scheme. As will be demonstrated in this paper, the adaptive impedance telehaptic control scheme is significantly more robust with respect to an increase in time delay, ensuring a better overall telehaptic perception of delayed stiffness as compared to state-of-the-art transparentizing force-position teleoperation methods.

The rest of the paper is organized as follows. Section 2 describes the basic theoretical aspects of the proposed adaptive impedance telehaptic scheme regarding the design of the parameter adaptation law. Section 3 describes the numerical experiments conducted to evaluate the transparency and stability properties of the telehaptic system in the presence of large time delays. The experimental analysis that was conducted to assess performance in terms of human telehaptic discrimination of linear stiffness in the presence of network delay is presented in Section 4, where the comparative benefit of the proposed adaptive scheme is analyzed statistically and discussed. Section 5 presents the second experimental study, performing a comparative evaluation of the proposed adaptive method with respect to a state-of-the-art transparentizing teleoperation scheme. Conclusive remarks and directions for future work are discussed in Section 6.

2 Adaptive Impedance Telehaptic Control: Theoretical Formulation

2.1 Telehaptic Control Scheme: Modelling

Figure 1 shows the overall architecture of the adaptive impedance telehaptic control scheme. For sim-

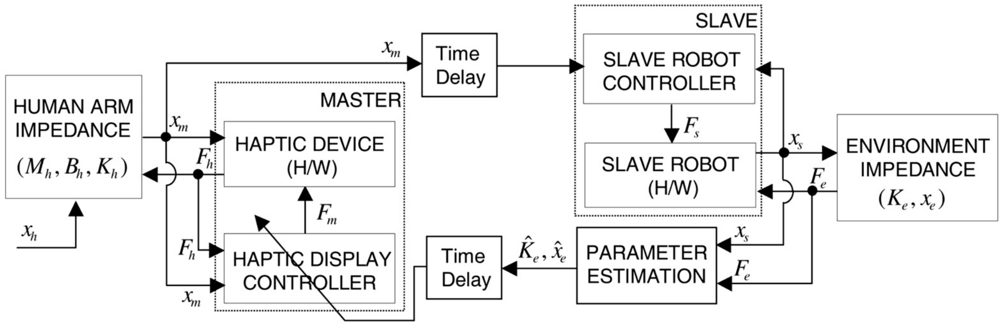


Figure 1. *Adaptive impedance telehaptic control scheme.*

ulation and theoretical analysis purposes, the human arm impedance is approximately modelled as a mass-spring-damper (M_h, K_h, B_h) system, described by the following linear dynamic equation:

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

where F_h is the force exerted on the human hand by the haptic device, X_h refers to the voluntary motion (desired position) issued by the human operator's sensorimotor system, and X_m represents the current position of the haptic master device. In this simplified linear model, it is assumed that the haptic device is held firmly by the human operator, meaning that the position of the human hand is assumed to be tightly coupled to the position of the haptic master (which explains why the mechanical impedance parameters of the human hand in this equation multiply the motion variables of the haptic master).

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

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

This equation models the local impedance (in this case, the local stiffness) of the slave robot environment, where K_e is the stiffness, x_e is the assumed contact equilibrium (rest) position for the modelled spring forces applied by the remote environment on the slave robot, and 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, assuming relatively slow motion throughout the teleoperation task.

In direct position-force bilateral teleoperation systems, the force F_e is reflected directly on the master controller and is displayed via the haptic device 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 at the slave site of the telehaptic system, the physical characteristics (K_e, x_e) of the remote environment can be estimated online. The estimates $(\hat{K}_e, \hat{x}_e)$ are then reflected to the master station and used to compute the forces displayed to the human operator. As already mentioned, the goal of such an adaptive "impedance reflecting" telehaptic scheme is in fact to decouple, in a way, the master and slave systems, enabling the human operator to interact haptically with a locally emulated (but continuously adapted) model of the remote environment. 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, then, to ensure the quality of the system's transparency; that is, the matching between the impedance perceived by the human operator and the real physical properties of the remote environment.

2.2 Online 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 rest 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 on the human operator by the haptic display controller are, thus, computed using estimated impedance values ($\hat{K}_e$ and $\hat{x}_e$):

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

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 online estimate of the actual remote impedance characteristics (K_e, x_e), where the goal is to minimize the force estimation error, defined as:

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

$\hat{F}_e$ 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 online. Let us define the impedance parameter vector as:

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

where $F_0 \triangleq K_e \cdot x_e$. The estimated reaction force in Equation 5 can then be 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 $\hat{\theta}_e$ is 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 $\tilde{\theta}_e$ is the impedance parameter estimation error:

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

Let us now assume a general adaptation law of the form:

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

where $\gamma_\theta = [\gamma_{\theta 1}, \gamma_{\theta 2}]^T$ is a vector containing adaptation gains, and e_f can be interpreted as the observation (output) error signal (in this case, the error between the estimated and the actual measured force applied on the slave robot). In previous work (Tzafestas et al., 1997, 2008), it was shown that the adaptation gains can be designed as follows:

$$\gamma_\theta = \Gamma_e^{-1} \cdot \begin{bmatrix} -x_s \\ 1 \end{bmatrix}, \tag{12}$$

where Γ_e is defined as a symmetric, positive-definite (2×2) matrix. By applying Lyapunov stability analysis and LaSalle's principle, it can be shown that, by designing the adaptation gains as in Equation 12, the force estimation error converges to zero (Tzafestas et al., 2008). This result, though, does not guarantee global asymptotic stability and convergence of the parameter estimation error. As in any system identification strategy, persistent excitation is needed to ensure that the estimated parameters will converge to their true values. Nevertheless, it is argued that fast and stable convergence of the force estimation error to zero suffices to reliably reconstruct the perceived impedance, achieving high transparency for the telehaptic system. Furthermore, the above adaptation law can be robustly tuned, achieving a fast convergence rate, as demonstrated in previous work (Tzafestas et al., 1997, 2008).

2.3 Computing Updates of Impedance Parameters

From Equation 8 we have:

$$\dot{\hat{\theta}}_e = \begin{bmatrix} \dot{\hat{K}}_e \\ \dot{\hat{F}}_0 \end{bmatrix} = \begin{bmatrix} \dot{\hat{K}}_e \\ \dot{\hat{K}}_e \cdot \hat{x}_e + \hat{K}_e \cdot \dot{\hat{x}}_e \end{bmatrix}. \tag{13}$$

If we take Γ_e to be diagonal:

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

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

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

the adaptation law for the impedance parameters (K_e, x_e) can then be written, by combining Equations 11, 12, and 13, as:

$$\begin{bmatrix} \dot{\hat{K}}_e \\ \dot{\hat{K}}_e \cdot \hat{x}_e + \hat{K}_e \cdot \dot{\hat{x}}_e \end{bmatrix} = - \begin{bmatrix} \gamma_{e1} & 0 \\ 0 & \gamma_{e2} \end{bmatrix} \cdot \begin{bmatrix} -x_s \\ 1 \end{bmatrix} \cdot e_f, \tag{14}$$

from which we finally get:

$$\dot{\hat{K}}_e = \gamma_{e1} \cdot x_s \cdot (\hat{F}_e - F_e), \tag{15}$$

and

$$\dot{\hat{x}}_e = \frac{(\hat{F}_e - F_e)}{\hat{K}_e} \cdot (-\gamma_{e2} - \gamma_{e1} \cdot x_s \cdot \hat{x}_e). \tag{16}$$

Equations 15 and 16 are used to compute online updates for the estimates of the (slave robot's environment) impedance parameters $(\hat{K}_e, \hat{x}_e)$. These estimates are continuously communicated to the master haptic display controller, as shown in Figure 1, and constitute the local impedance model used to compute the forces applied to the human operator according to Equation 3.

3 Characterization of Transparency and Stability: Numerical Experiments

A first set of numerical experiments was conducted with the object of assessing the performance of the proposed adaptive impedance telehaptic system from a control perspective. In particular, the stability and the achieved transparency of the bilateral teleoperation system is characterized considering variable time delay and environment stiffness.

3.1 Experimental Setup and Procedures

The overall experimental system used in this analysis is composed of two computer stations: (1) the master controller computer that performs all operations related to haptic display and control of the master device, as well as communication via the network with the remote (slave) system; and (2) the slave controller computer, which is a remote computer in charge of controlling the slave robot, receiving command signals from the master station, and reflecting feedback information including updates of the estimated impedance parameters as described in the previous section. Data exchange between the two control stations is done via a network protocol, which in these experiments is based on TCP/IP sockets. In this set of numerical experiments, a simulated slave system was used (running on the slave computer station), consisting of a single (linear) axis robot model in potential contact with a virtual wall (of linear stiffness K_e and rest position x_e).

3.1.1 Master–Slave Communication and Time Delay. The master and slave computers are connected via a local area network, exchanging data on a shared port. 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 and write data streams on a shared port. The data that the master computer transmits is, in our case, simply the current position x_m of the haptic device (simulated, in this case, or real). Accordingly, the data that is sent back by the slave consists of: (1) the force F_e experienced by the (in our case, simulated) slave robot, (2) the current position x_s of the slave robot, and (3) the estimated impedance parameters $(\hat{K}_e, \hat{x}_e)$ of the slave environment.

To introduce and emulate a variable time delay in the master–slave communication loop, we use a buffering algorithm. Data is temporarily stored in a buffer (which operates, 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.

3.1.2 Modelling Assumptions. At this series of numerical 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 slave computer and the simulated slave robot environment. The emulated motion at the haptic interface consists of a linear, constant velocity movement, 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 Figure 1). The parameters of the human arm impedance model were set as: $M_h = 1$ kg, $B_h = 20$ Ns/m, and $K_h = 160$ N/m (regarding the simulated dynamics of the human arm, these values correspond to a time constant of approximately 0.1 s and a damping coefficient $\zeta \approx 0.8$). 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 rest position $x_e = -0.2$ m, with stiffness (where not otherwise mentioned) $K_e = 200$ N/m.

3.2 Definition of Transparency and Stability Measures

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 of the remote environment actually is. In our case, the remote 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 telehaptic system, we can compute the distance of all (x_m, F_m) sample points (with $x_m < x_e$) from the above line equation (ideal linear stiffness). The distance of any point $(x_m^{(i)}, F_m^{(i)})$ $(i = 1, \ldots, N)$ from the 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:

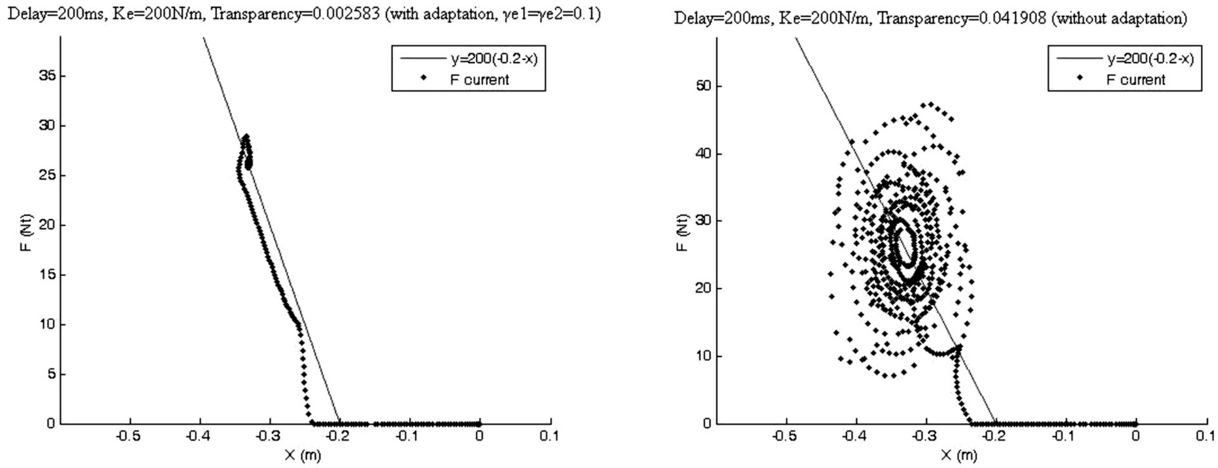
$$d_i = \left| \frac{x_m^{(i)} \cdot A + F_m^{(i)} \cdot B + C}{\sqrt{A^2 + B^2}} \right|. \qquad (17)$$

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

$$\text{Transparency} = \frac{1}{N} \cdot \sum_{i=1}^{N} d_i. \qquad (18)$$

Regarding stability, we also need to define an objective measure that can be easily computed from the observed data. The goal at this point is not to apply a theoretical stability analysis method, but instead, to evaluate experimental stability margins by performing an analysis of the results obtained during a series of numerical experiments, for different values of the parameters explored (time-delay, environment stiffness, and control method used). The algorithm used for this purpose aims to analyze the transient response (in the time domain) of the simulated closed-loop (1-DOF) telehaptic system in a steplike input, in order to detect in which case the system becomes unstable. Instability is typically characterized experimentally by the presence of sustained oscillations in the system's response, which can be evaluated quantitatively to judge the occurrence of such an event in the experimental data, as described below. A similar approach has also been followed in several other works evaluating experimental stability boundaries, for instance in the work of Hulin, Gil, Sanchez, Preusche, and Hirzinger (2006) and Diaz, Gil, and Hulin (2010), where an experimental stability analysis of a haptic system was conducted, evaluating dimensionless stability boundaries by experiments and estimating limit stable parameter values in a relevant context.

In experimentally assessing stability, we thus consider the capacity of the system (in this case, the simulated haptic master) to settle to a steady state, after the introduction of an external disturbance (in this case, after contact of the simulated slave robot with its virtual environment). For the numerical experiments conducted in this study, an experimental measure of stability is defined as follows: the response of the system, defined as the actual haptic master position, is recorded for an initial and a final time interval, and then two sums of squared distances are computed (values SSD_1 and SSD_2, respectively) of these recorded positions from their respective interval mean value. The first interval was composed of the initial 2 s after application of a feedback force $(F_m > 0)$, and the second interval was composed of the last 2 s of the simulated motion. If $SSD_2 < \lambda \cdot SSD_1$ $[\lambda \in (0, 1)]$, then the system's response is considered to exhibit some asymptotic convergence properties (i.e., the oscillatory response pattern progressively vanishes out to a settling point), and the system is characterized as stable (in our case we chose $\lambda = 0.5$); otherwise, the system is considered to be unstable, exhibiting sustained oscillations in the observed output. Numerical simulations were conducted for increasing stiffness K_e and time delay. For each value of the time delay, a critical



(a) *With adaptive impedance telehaptic control* (b) *Direct teleoperation (without adaptive control)*

Figure 2. *Simulated master force-position response (with delay = 200 ms) with respect to the ideal transparency (linear stiffness): (a) with the proposed adaptive impedance telehaptic control and (b) with direct teleoperation control (without adaptive control).*

stiffness K_c was identified, corresponding to a maximum stiffness value below which the system remains stable (that is, for $K_e > K_c$ the system becomes unstable). Comparative numerical results are presented in the following section.

3.3 Analysis of Stability and Transparency: Numerical Results

Figure 2 shows a sample of the results obtained (with delay = 200 ms) regarding the simulated master force-position response with respect to the ideal transparency, comparatively: (1) with the application of the proposed adaptive impedance telehaptic control scheme, and (2) without the proposed adaptive control, by applying a typical direct (position/force) teleoperation controller. The adaptive impedance telehaptic scheme is applied as described in Section 2 (with $\gamma_{e1} = \gamma_{e2} = 0.1$). In both control cases of Figure 2, the same simulated voluntary human hand motion is considered as the input of the telehaptic system, referred to as x_h in Equation 1, which consists of a ramp-like motion, that is, a linear, constant velocity movement until a specific penetration depth is reached inside the simulated surface (in this example, of assumed stiffness $K_e = 200\ N/m$). The hysteresis-like form of Figure 2(b) (with multiple apparent movements) is due to the oscillations at the actual (simulated) haptic master position, caused by the presence of time delay and the consequent loading-unloading movements that occur. The value of the transparency measure obtained in this case is 0.041908. It is apparent from the results depicted in Figure 2(a) that the activation of the proposed adaptive scheme eliminates this undesirable effect and achieves a force-position response that approaches the desired stiffness line (the transparency measure achieved in this case is reduced by an order of magnitude and has a value of 0.002583).

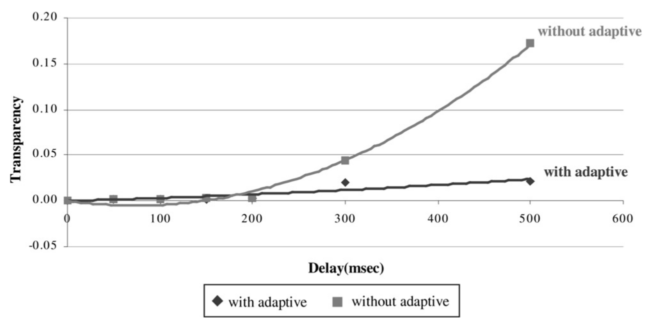


Figure 3. *Comparative numerical results regarding transparency, for increasing delay (K_e = 200 N/m).*

The overall comparative results regarding transparency and stability are depicted in Figures 3 and 4,

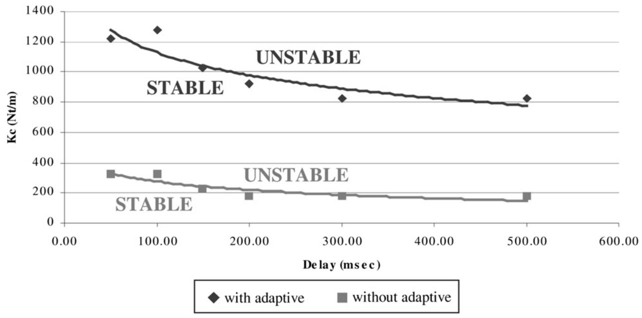


Figure 4. *Comparative numerical results regarding stability margin, for increasing time delay.*

(a) *Master Site* (b) *Slave Site*

Figure 5. *Setup for the telehaptic experiments.*

respectively. A global conclusion that can be drawn from these graphs is that the teleoperation control stability margin increases significantly when the adaptive impedance scheme is applied. We can observe, though, that below the stability margin, the two controllers (shown as either with or without the proposed adaptive scheme) perform similarly in terms of transparency. However, a time delay of 300 ms or more (for $K_e = 200$ N/m) quickly destabilizes direct teleoperation, leading to a significant deterioration of system transparency. This result demonstrates the superior performance of the adaptive impedance telehaptic scheme, as clearly shown in Figures 3 and 4.

4 Telehaptic Discrimination of Delayed Stiffness: Psychophysical Experimental Analysis

The ultimate goal of a telehaptic control system is to reliably convey touch-related sensations, enabling the human operator to accurately perceive the physical properties of a remote environment. To analyze the actual performance of the telehaptic system, as related to human perception of a real slave-robot remote environment, we performed a set of psychophysical experiments. This section presents the experimental evaluation study conducted to assess, in particular, the telehaptic perception (discrimination) of real (remote) stiffness under time delay, when applying the proposed adaptive impedance scheme.

4.1 Experimental Setup

The experimental setup and hardware configuration of the telehaptic system used in this study are depicted in Figures 5 and 6. Apart from the master and slave computer stations, which are identical to the numerical analysis of the previous section, the system is composed of, in this case, two real haptic devices as master and slave robots.

4.1.1 Master Haptic Device. A PHANToM Omni device was used at the master haptic interface. This device captures motion (position and orientation in three dimensions) of the human hand manipulating the handle and displays forces in three dimensions. The device communicates with the master computer via a USB port.

4.1.2 Slave Robot Device. A PHANToM desktop haptic device was used as the slave robot. This device can move in three dimensions. It was slightly modified to be used as the slave robotic manipulator. Its handle was attached on the second link (since the revolute joint between these two mechanical parts is not actuated), and a tactile sensor (PPS ConTacts C500) was attached on the tip of the second link, in order to measure the force exerted during its interaction with the remote environment. The sensor is connected to a DAQ device (National Instruments NI USB-6009) which communicates with the slave computer via a USB port. The PHANToM desktop device communicates with the slave computer via a parallel port.

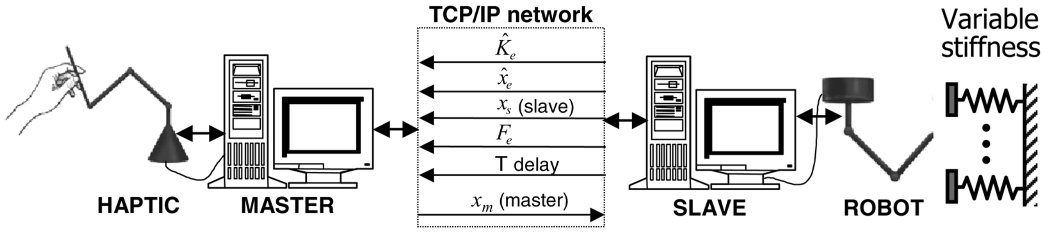


Figure 6. *System configuration for the telehaptic experiments.*

The master and slave computers are again connected via a local area network, exchanging data on a shared port (via TCP/IP sockets) using the same client-server communication protocol. The data that the master computer transmits is, in this case, simply the current position x_m of the haptic device. Accordingly, the data sent back by the slave station is composed of the force F_e measured at the slave robot and its current position x_s. When the adaptive impedance telehaptic control scheme is active, this data also includes the current estimated impedance properties of the remote physical environment. The remote environment consisted of a set of four vertically placed linear springs with different stiffness coefficients. Network delay was again emulated using the same buffering algorithm as in the previous section. It is worth noting that a minimal time delay always exists, introduced by data transfer and handling in the TCP/IP communication loop between the haptic master and slave computers in the LAN setting. A set of measurements showed that the average round-trip value of this delay in our telehaptic setup was approximately 2 ms, with a peak value of approximately 5 ms.

Regarding the user interface at the master station, along with the application window providing information on the current state of the experimental trial, an additional simple graphical interface was used, visualizing the current haptic device velocity as a colored vertical bar. The length of the bar was proportional to the magnitude of the velocity, and a color change (from green to red) illustrated when its magnitude went below a certain limit. Graphic display was done using simple (2D) OpenGL commands and was meant to discourage the subjects from probing too slowly (thus, from artificially reducing the influence of time delay). As a lower limit, we imposed a velocity of 30 mm/s. In order to avoid probing a spring beyond its physical limit, an auditory cue was also provided when the maximum allowed level of spring deformation was reached. No other visual information was provided to the subjects during probing (loading-unloading) movements, in order to avoid any effects of visual-haptic asynchronies as reported in Di Luca, Knörlein, Ernst, and Harders (2011).

Limitations were imposed on the subjects during probing (in terms of the velocity of movement as well as the number of probes allowed) in order to minimize the potential influence of any factor other than the explicit difference in the experimental condition related to the control method and the time delay. In particular, the limitation in probing velocity (which was implicitly imposed in the experiments through instructions given to the subjects during the training sessions and the visual cues described above) was chosen to minimize the effect that a very slow probing velocity may have in counterbalancing the presence of time delay in the control loop. Our aim was to systematically assess the effect of the telehaptic control method and to eliminate or balance the impact of any other potentially influential factor. Imposing such systematic constraints in the experimental protocol is in line with similar observations reported in Nisky et al. (2008), where the probing strategy used by subjects (including probing velocity and number of probing motions) is found to influence perception. Subjects were thus instructed to perform rapid probing movements, since it is apparent that very slow probing velocities may alter the effect of time delay.

4.2 Experimental Protocol

Two series of experiments were conducted. In both experiments, a forced-choice psychophysical protocol was applied, similar to the protocol used in the work of Nisky et al. (2008). A seated subject held his or her dominant hand on the handle of the master haptic device and performed each trial watching the monitor of the master controller computer, which provided information about the state of the experiment and the probing velocity, as explained previously. In each trial, subjects were presented with two springs and were asked to choose which of them was stiffer by (telehaptically) probing each one of the (remote) fields five times at most. Subjects were asked to probe one of the fields first, then switch to the second one by pressing the space button on the keyboard with the free nonprobing hand. Once the users were ready, they were asked to state which field felt stiffer by pressing the appropriate button on the keyboard. One of the fields, for all trials, was the reference field and always had a nominal stiffness of 117.72 N/m. The other was the stimulus field and its stiffness varied between three nominal values: 78.48, 137.34, and 206.01 N/m. Each pair of reference and stimulus fields was considered as a single test trial. The order of appearance of these two fields in each test trial was randomized. Prior to the test trials, every subject carried out a set of training trials in order to learn to make rapid movements, keep the hand in motion while inside the field, keep the probing velocity above the limit and avoid passing the physical limit of the field (i.e., the minimum working length of the spring). The subjects performed 10 training trials before the actual test trials.

The two series of experiments conducted were thus organized as follows.

4.2.1 Delayed Stiffness and Impedance Adaptation. Twenty subjects participated in this experiment. Two subjects were excluded due to their low probing velocities. Each subject performed 18 test trials with impedance adaptation ($\gamma_{e1} = \gamma_{e2} = 0.1$) and 18 without impedence adaptation (i.e., with direct teleoperation control), in two separate sessions. The time delay in these trials was fixed to 100 ms (note that this delay value was chosen so that the direct teleoperation system remained theoretically stable, with all experimental stiffness values well below the critical stiffness stability margin, as numerically demonstrated in the previous section). In every session, each of the three stimulus fields was presented six times randomly. It is worth noting that, in this experiment, time delay was introduced in both reference and stimulus fields. The goal was to measure discrimination ability within a delayed stiffness field; so, both fields in each trial were displayed with the same amount of delay present, in order to measure to what extent the capacity of the subject to detect variations within a stiffness field may be affected by the presence of time delay in the field.

4.2.2 Non-Delayed Stiffness and Direct Position-Force Teleoperation. Twenty-one subjects participated in this experiment. Each subject performed 18 test trials. During these trials, force feedback both for the stimulus and the reference fields was not delayed. In every session, each of the three stimulus fields was presented six times randomly. No adaptive control scheme was involved in the force-position signal flow. This experiment was, in fact, performed as a means to provide what could be considered as the benchmark perceptual performance in the nondelayed case for the haptic teleoperation experimental setup used in this study.

4.3 Data Processing Techniques

4.3.1 Psychometric Curves. We followed a data processing procedure to compute stiffness discrimination thresholds, similar to the procedure followed in the work of Nisky et al. (2008). The task of comparing two springs by probing them is a psychophysical discrimination task. A common method to quantify a subject's performance in such a task is the psychometric curve. The psychometric function relates the subject's responses to an independent variable, usually some physical measure of the stimulus (Wichmann & Hill, 2001). The general form of a psychometric function is:

$$\psi(x, \alpha, \beta, \gamma, \lambda) = \gamma + (1 - \gamma - \lambda) \cdot F(x, \alpha, \beta), \quad (19)$$

where x is the physical property of the stimulus. The shape of the curve is determined by the parameters $[\alpha, \beta, \lambda, \gamma]$ and the choice of a two-parameter function F, typically a sigmoid.

We derived the psychometric functions by, firstly, estimating points on the curves. Every point on the curve represents the subject's probability of answering that the stimulus is stiffer as a function of the actual difference $\Delta K = K_{\text{stim}} - K_{\text{ref}}$, where K_{stim} and K_{ref} denote the stiffness of the stimulus and reference field, respectively. This probability was calculated from the following equation:

$$P(\Delta K) = \frac{\sum_{n=1}^{N(\Delta K)} A[n]}{N(\Delta K)}, A[n] = \begin{cases} 1 & \text{stimulus stiffer} \\ 0 & \text{reference stiffer} \end{cases}, \tag{20}$$

where $A[n]$ is a binary representation of the subject's answer, and $N(\Delta K)$ is the total number of trials with given stiffness difference ΔK. Then, the *psignifit toolbox* (version 2.5.6 for MATLAB; Wichmann & Hill, 2001) was used to fit the psychometric curves to the points calculated from Equation 20.

4.3.2 JND. After the fitting of the psychometric curves, the JND values were computed, using the following equation:

$$JND = \frac{F^{-1}(0.75) - F^{-1}(0.25)}{2}. \tag{21}$$

The values computed from the above equation provide a quantitative measure of human haptic perception ability, and were used to evaluate the effect of time delay and controller choice.

Table 1. *JND Values (N/m) of Individual Subjects for Delayed and Nondelayed Trials*

Delayed trials			Nondelayed trials	
	Adaptive	Direct		Direct
Subject	JND	JND	Subject	JND
1	26.5414	1.4902	1	45.6493
2	45.6737	26.5414	2	26.4682
3	1.4902	40.5640	3	29.3122
4	1.4902	95.7224	4	1.4902
5	46.1901	44.8941	5	63.8118
6	57.4314	56.2705	6	65.8722
7	26.5414	89.5349	7	24.3778
8	70.3031	29.3422	8	63.8118
9	1.4902	70.3031	9	43.0270
10	24.3789	29.4723	10	2.7981
11	30.2837	40.5640	11	44.8846
12	19.5094	36.8472	12	26.4682
13	29.3422	46.1901	13	29.3122
14	1.4902	29.3422	14	43.0270
15	30.2837	57.4314	15	40.5403
16	30.2837	40.5640	16	30.2682
17	63.8203	65.8908	17	30.2682
18	44.8941	63.8203	18	1.4902
Mean JND	30.6354	48.0436	19	2.7981
			20	25.8385
			21	35.8770
			Mean JND	32.2567

4.4 Experimental Results and Discussion

During each session in all the experimental cases, the subjects' responses and probing velocities were recorded. All subjects reported that they felt confident about their answers in most of the trials. Psychometric curves were fitted to the responses of each individual subject, in three distinct experimental conditions: (1) delay with adaptive impedance control, (2) delay with direct position/force teleoperation control (i.e., without adaptive control), and (3) no delay with direct control (i.e., without adaptive control). From the psychometric curves fitted to these experimental data, the JND values were computed reflecting performance related to stiffness perception. Table 1 shows these JND values (in N/m) computed for each individual subject, for both delayed and nondelayed experiments and for the three different experimental conditions. A subject's JND provides an assessment of perceptual uncertainty, that is, the ability to discriminate differences in the value of a stimulus (in this case, stiffness variations). In Table 1, we clearly see that in the delayed trials with adaptive control, there is a general decrease in the JND values as compared to the delayed trials with direct control. This finding indicates that the discrimination ability of the subjects is clearly improved with the use of the proposed adaptive impedance control scheme.

Table 2. *JND and Weber Fraction for Telehaptic Perception of Stiffness, Obtained in the Three Considered Experimental Conditions (Reference Stiffness 117.72 N/m and Delay, when Present, 100 ms)*

Experimental condition	JND ± *SD* (N/m)	Weber fraction
1. Delayed adaptive	31 ± 21	~26%
2. Delayed direct	48 ± 23	~41%
3. No delay (direct)	32 ± 19	~27%

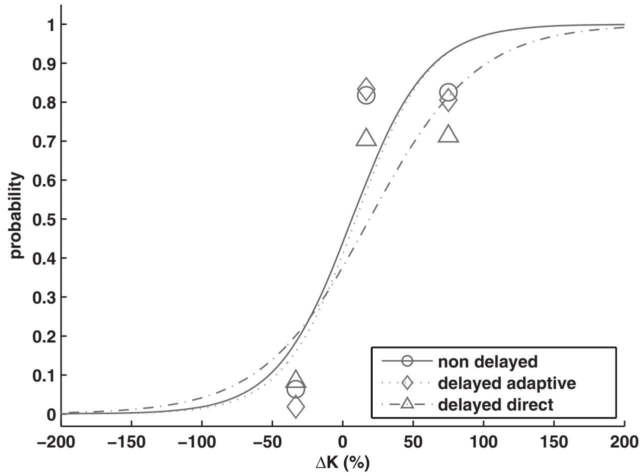


Figure 7. *Psychometric curves fitted to the pooled subject data in the three experimental cases.*

The average JND values (mean and standard deviation) together with the respective mean Weber fractions (from all the individual subject data) are also shown in Table 2, comparatively for the three different experimental conditions. These average JND values are found to be approximately 31 ± 21 N/m and 48 ± 23 N/m (mean ± standard deviation), for the delayed trials with and without adaptive impedance control, respectively (mean Weber fractions: 26% and 41%, respectively). A JND value of approximately 32 ± 19 N/m (mean Weber fraction: 27%) was computed for the nondelayed trials with direct (no adaptive impedance reflection) control.

The obtained experimental data (correct responses) were also pooled for all subjects, in the three considered experimental conditions, and are shown in Table 3 (where $\Delta K_1 = 0.75K_{\text{ref}}$, $\Delta K_2 = -0.33K_{\text{ref}}$, $\Delta K_3 = 0.17K_{\text{ref}}$). The psychometric curves that were fitted on the pooled data in these three experimental conditions are shown in Figure 7. These results demonstrate that the slope of the fitted sigmoid function in the case of the delayed stiffness without adaptive control (delayed, direct condition) is apparently decreased as compared to the slope of the curves fitted in the other two experimental conditions (i.e., delayed trials with adaptive control and nondelayed trials). This experimental finding obviously reflects the increased difficulty that the subjects experience when having to (telehaptically) probe and assess the stiffness of a (remote) linear spring in the presence of a delayed reflected force field, when the adaptive impedance telehaptic control is not active.

To further assess the significance of these differences in the JND values between the three different experimental conditions, a statistical analysis (t-test) was performed. The difference between the JND values obtained in the two delayed conditions (adaptive vs. direct control) is found to be statistically significant, paired t-test, $t_{18} = -2.3$, two tailed $p = .036$, while the slight difference between the delayed adaptive and

Table 3. *Averaged Experimental Data for All the Subjects in All the Experimental Conditions*

	Correct responses (%)								
	1. Delayed adaptive			2. Delayed direct			3. Nondelayed (direct)		
	ΔK_1	ΔK_2	ΔK_3	ΔK_1	ΔK_2	ΔK_3	ΔK_1	ΔK_2	ΔK_3
Mean	98.15	83.33	80.56	91.67	70.37	71.30	93.65	81.75	82.54
SD	5.39	17.15	18.30	11.79	29.46	15.97	7.68	14.29	15.39

the nondelayed (direct) conditions is not, two-sample t-test for unequal sample sizes and unequal variances, $t_{37} = 0.25$, two tailed $p = .801$. Furthermore, as could have been anticipated, the increase of the JND values (implying haptic perception degradation) in the second experimental condition (delayed, direct control, without impedance adaptation) with respect to the third experimental condition (nondelayed, direct teleoperation control) is also statistically significant, two-sample t-test for unequal sample sizes and unequal variances, $t_{35} = 0.25$, two tailed $p = .022$.

The above experimental results clearly demonstrate that, in the presence of large and unknown time delays, the proposed adaptive impedance scheme presents superior performance, in terms of human telehaptic perception, as compared to direct position-force teleoperation control. It is reasonable, however, to assume that the best perception of a remote environment is achieved when there is no delay in the data transfer between master and slave stations. Direct force-reflecting teleoperation in these nondelayed trials corresponds to a benchmark performance, providing an indication of the inherent mechatronic limitations of the system. Further observation of the results depicted in Figure 7 reveals that the psychometric curve fitted to delayed trials, obtained with the proposed adaptive impedance telehaptic controller active, seems to nearly coincide with the one obtained in the nondelayed (direct teleoperation) trials. This experimental finding, in addition to the previous results regarding the JND values, shows that the proposed adaptive impedance telehaptic controller seems to mitigate some of the problems caused by the network delay, leading to an actual performance (in terms of perceptual sensitivity) that is comparable to the benchmark performance achieved in the direct nondelayed experimental condition.

At this point, a further analysis of the obtained results is needed, to evaluate the influence that the order of appearance of the controller had on the perceptual performance of the subjects. As already mentioned, in the first series of psychophysical experiments (composed of the first two experimental conditions), the controller was involved randomly in the first or in the second half of the trials. Therefore, the results obtained in the first two experimental conditions (i.e., the JND values of the delayed trials) are separated into four subgroups. These four subgroups are named: JND0_1, JND0_2, JND1_1, and JND1_2, where the first digit indicates the teleoperation controller type (0: no adaptive control, 1: with adaptive impedance control), and the second digit indicates the order of appearance (1: 1st in the experimental series, and 2: 2nd in the experimental series). To see whether the differences between groups are significant, we applied ANOVA analysis to the data. The p-value between the groups is found to be .0043 ($p < .01$). This result indicates that there are indeed significant differences in the JND values between the groups.

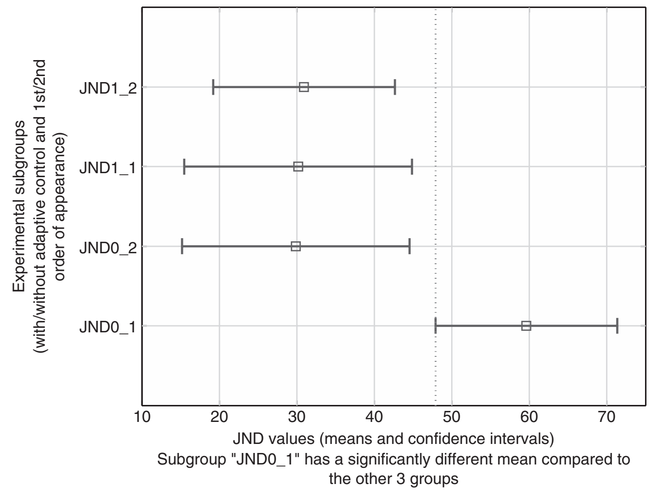


Figure 8. *Tukey's HSD test for the JND values.*

To further explore these differences, we applied Tukey's HSD test to the four groups of JNDs. Figure 8 shows the results of the test (the mean of each group and the 95% confidence intervals). From this figure we conclude that the mean value of the JND0_1 group is significantly different from mean values of the other groups, since their respective confidence intervals are disjoint. This finding highlights again the statistically significant deterioration of telehaptic perception performance (significantly higher JND value) resulting from the presence of time delay, when the proposed adaptive impedance scheme is not active. This performance degradation is evident when the subjects begin their trials in the absence of the proposed adaptive impedance controller. Perceptual sensitivity is significantly improved, though, when the proposed adaptive controller is activated. Surprisingly, this improvement in perception performance seems to persist (similar to a memory or learning effect) even after this controller becomes inactive again (i.e., in the case of Group JND0_2). All these experimental findings validate the argument that an adaptive telehaptic control scheme, like the one proposed in this paper, can indeed consistently reduce the negative effects of network delays in a bilateral teleoperation system, improving perceptual performance at a level comparable, in a way, to nondelayed situations.

5 Comparative Experimental Evaluation of Psychometric Transparency

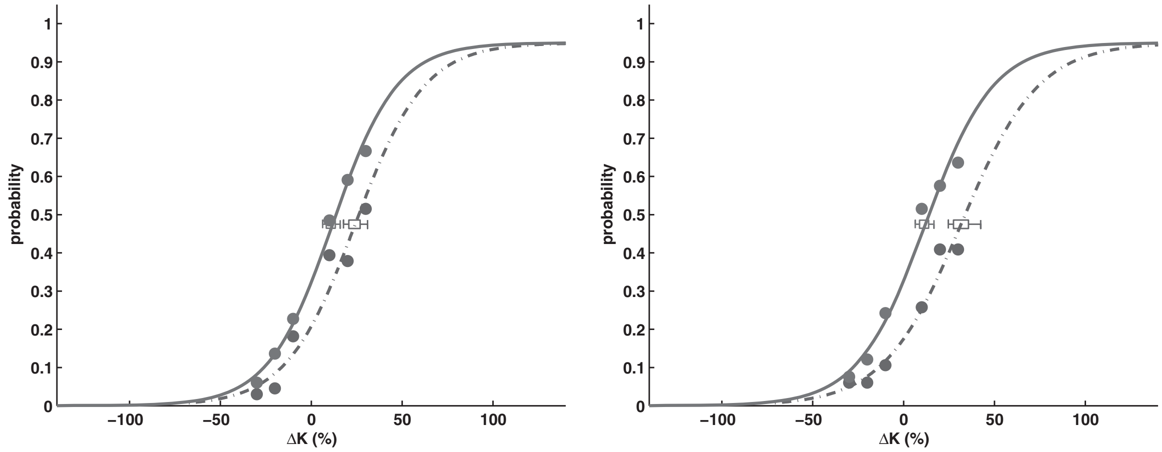
In order to further assess the kinesthetic performance of the proposed telehaptic control scheme with respect to state-of-the-art approaches for transparent teleoperation under time delay, we performed a comparative experimental analysis, evaluating the proposed adaptive control scheme with a method proposed recently in Nisky et al. (2011). In this work, Nisky et al. employ a so-called transparentizing controller to cope with similar time delay problems and maintain perceptual and motor transparency during a soft-tissue teleoperated needle-insertion task (also assuming a linear springlike force field). Psychomotor and psychometric transparency is evaluated in terms of the PSE (Point of Subjective Equality) values, obtained when fitting psychometric curves on subject responses during psychophysical experiments, indicating the presence of stimulus underestimation or overestimation (PSE values positive or negative, respectively). Psychomotor performance is not relevant in our work, since no teleoperation task is considered that involves positioning accuracy (instead we focus on performance related to the quality of telehaptic perception). Thus, the experimental analysis in this section focuses on comparatively evaluating psychometric transparency, by measuring differences in PSE values under different time delay conditions and choices for the control scheme.

In the sequel, the proposed adaptive control scheme is termed the adaptive method, while the transparentizing control method from Nisky et al. (2011) is termed the transparentizing method. In this method, a simple transmission line model is assumed, involving position and force feedback gain, as well as a communication delay, where the total transmission gain is unity, that is, $G_x = 1/G_f$ (where G_x, G_f are the position and force gains, respectively). In our experiment, we chose $G_x = 0.9$, which is the median of the position gains of all subjects from the second experiment reported in Nisky et al. To explore the effectiveness of both methods, the following experimental evaluation approach was used: we performed a series of probing trials with time delay, where the proposed adaptive control scheme was present in half of them, and the transparentizing method was utilized in the rest of the trials. Two different time delays were used, 50 ms and 80 ms, in equal number of trials. The values of time delay were chosen within a margin that maintains stability of the transparentizing method as reported in Nisky et al. Time delay was again emulated using a buffering algorithm. The (virtual) environment consisted of a linear spring with a stiffness coefficient between 0.05 and 0.11 N/m. The stiffness levels were also chosen to be consistent with the range of values used in Nisky et al.

5.1 Experimental Protocol

The experimental setup used in this case study uses an Omni device as the haptic master interface. The master controller runs on a PC that performs all operations related to the computation of feedback forces, communication, and control of the haptic interaction device, as well as control of the virtual environment and execution of the buffering algorithm when necessary. The slave environment is in this case simulated, composed of a haptic probe and virtual linear springs with a range of stiffness values mentioned in the previous section.

During the experiment, a seated subject held with his or her dominant hand the handle of a PHANToM Omni haptic device and manipulated it to feel the virtual environment. A forced-choice procedure was once again employed. In each trial, subjects were presented consecutively with two springs and were asked to indi-



(a) *Time delay* 50ms

(b) *Time delay* 80ms

Figure 9. *Psychometric curves fitted to all subjects' answers (solid line: adaptive method; dashed line: transparentizing method).*

cate which one felt stiffer by exploring each one for as long as they wished. They were asked to explore one of the springs first and then, when they felt ready, to switch to the second spring by pressing the upper button of the Omni stylus; then the second spring was explored, and once the users felt confident, then they switched to the answer mode by pressing the same button and made their choice by pressing the appropriate numeric button on the keyboard (1 or 2). Subjects were not able to explore the springs for a second time in the same trial. One of the springs was the reference spring with a stiffness coefficient equal to 0.08 N/mm. The other was a comparison spring with a stiffness coefficient selected among three smaller and three larger neighboring sizes: 62.5%, 75%, 87.5%, 112.5%, 125%, and 137.5% of the reference stiffness. The order of appearance of reference and comparison stimuli in each trial was random. Each pair of stimuli was considered as a single test trial. Prior to the test trials, every subject carried out some training trials in order to become acquainted with the experimental setup. In each training trial, a pair of reference and comparison stimuli was presented, chosen randomly among the possible pairs. The subjects performed 10 training trials before the test trials.

The experiment conducted was thus organized as follows. Thirty-three subjects participated in the experiment. Each subject was presented randomly with all of the possible combinations of reference and comparison springs two times per condition (i.e., time delay and control method used). Every subject performed in total 48 test trials. Half of the trials (i.e., 24 trials) were performed with the adaptive method used, while the rest were performed with the transparentizing method. For each control condition, half of the trials (12 trials) were performed with time delay of 50 ms and the other half with the larger time delay of 80 ms. The order of appearance of the control conditions and time delays in each experimental session was fully randomized. Time delay was present only during haptic exploration of the comparison stimuli (the reference stiffness was always nondelayed and was displayed with direct position/force teleoperation control).

5.2 Experimental Results

As described above, the effectiveness of the two methods was compared in terms of the PSE values for a human subject kinesthetically exploring a virtual springlike environment via a haptic interface. During the experiments, the responses of the subjects were recorded. The psychometric curves fitted to the total responses of all subjects (percentage of cumulative correct answers per comparison stimulus) are shown in Figures 9(a) and 9(b), for time delay equal to 50 ms

Table 4. *PSE Values (N/m) Extracted from the Psychometric Curves Fitted to the Responses of All Subjects [Figures 9(a) and 9(b)], for Two Control Methods (Adaptive vs. Transparentizing) and Two Time Delay Values (50 ms and 80 ms)*

Adaptive		Transparentizing	
Delay = 50 ms	Delay = 80 ms	Delay = 50 ms	Delay = 80 ms
11.72	12.01	24.19	31.65

and 80 ms, respectively. In both figures, it is clearly seen that the proposed adaptive method results in a much lower PSE value than the transparentizing method. In particular, in the 80 ms case, the difference in the PSE values between the two methods is apparently significant, as shown by the clearly nonoverlapping confidence intervals depicted in Figure 9(b).

The PSE values extracted from both these curves are depicted in Table 4. For time delay equal to 50 ms, the PSE values obtained are 11.72 N/m for the adaptive method, and 24.19 N/m for the transparentizing method. For time delay equal to 80 ms, the PSE values are 12.01 N/m for the adaptive method, and 31.65 N/m for the transparentizing method. It can thus be concluded that a comparatively better telehaptic psychometric transparency is achieved when implementing the proposed adaptive impedance scheme. The adaptive method clearly mitigates, in an apparently more consistent way, the effect of time delay in stiffness perception, as indicated by the relatively small and almost constant PSE values obtained for both time delays, in contrast to the performance of the transparentizing scheme, where an increase in time delay causes a significant degradation of transparency, as can be assessed by the increase in the respective PSE value. This clear performance difference is also schematically illustrated in Figure 10.

The significance of these differences in PSE values can be evaluated by comparing the 95% confidence intervals of the psychometric curves fitted to the subjects' responses. Table 5 shows the bootstrap and the worst-case confidence interval limits (computed at .5 probability), for the different combinations of time delay and telehaptic control methods. From the results depicted in this table, it is clear that the PSE differences obtained for 80 ms time delay are indeed significant,

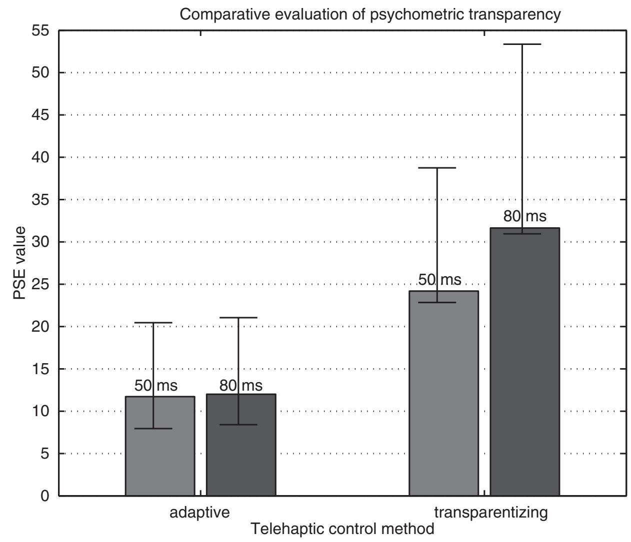


Figure 10. *Comparative psychometric performance, as measured by the PSE values obtained for the two tested control methods (adaptive vs. transparentizing) and two different time delays (50 ms and 80 ms). Bootstrap confidence intervals are also depicted (computed at .5 probability).*

as can be deduced by the almost nonoverlapping worst-case confidence intervals in this case.

In order to further assess the statistical significance of the above differences between the PSE values obtained in different experimental conditions, a t-test was carried out. For this purpose, the responses of all the subjects were randomly grouped in triplets, in order to obtain reliable computation of PSE values per individual subject group and to cope with the relatively small number of responses per subject and per combination of conditions in each individual trial (i.e., time delay, method used, and comparison stimuli). Analysis of the obtained results shows that the difference of the PSE values obtained for time delay equal to 50 ms from both methods is

Table 5. *Comparison of the Confidence Intervals Regarding the Psychometric Curves Fitted to the Subjects' Responses, for the Two Tested Control Methods (Adaptive vs. Transparentizing) and the Two Different Time Delays (50 ms and 80 ms).*

Delay	Method	Bootstrap limits		Worst-case limits	
		Min	Max	Min	Max
50 ms	Adaptive	7.94	20.46	6.51	26.47
	Transparentizing	22.84	38.75	21.99	47.47
80 ms	Adaptive	8.41	21.05	6.85	28.40
	Transparentizing	30.96	53.36	27.92	63.67

found not to be statistically significant, paired t-test, $t_{10} = -1.3806$, two tailed $p = .1975$. However, the difference in PSE values for time delay equal to 80 ms is indeed found to be statistically significant, paired t-test, $t_{10} = -3.1180$, two tailed $p = .0109$. Therefore, it is shown again that the proposed adaptive control scheme is significantly more robust with respect to an increase in time delay, ensuring overall a better telehaptic perception of delayed stiffness as compared to state-of-the-art force-position transparentizing control methods.

6 Conclusion

This paper focused on the application of an adaptive telehaptic control scheme, with the object of mitigating some of the problems associated with the presence of time delays in a teleoperation signal flow. Inspired by related work on concepts such as impedance-reflection and model-mediated telemanipulation, we propose to apply an adaptive impedance control structure at the slave site and to use the online estimation properties of such a controller to mediate the physical (impedance) characteristics of the slave robot environment, transmitting those back to the master station. The main issue in such a teleoperation architecture is to achieve fast and stable adaptation of the slave environment model, in order to ensure reliable reconstruction of its physical characteristics at the haptic master site.

In this paper, this adaptive impedance scheme is applied in a telehaptic perception context and is used to perform continuous online estimation of remote stiffness. Extensive numerical experiments were initially conducted to evaluate performance in terms of the trade-off achieved between transparency and stability, for which specific quantitative measures have been defined. The performance of the system is assessed considering the presence of variable time delay and increasing environmental stiffness. The numerical results clearly demonstrate that the adaptive impedance scheme exhibits superior performance compared to direct position-force teleoperation. Improved stability margins do not come at the expense of transparency for small time delays, whereas for large delays, the performance gain by the proposed scheme (both in terms of transparency and stability) is significant.

To further assess the actual performance of the adaptive impedance scheme in a real telehaptic task, we conducted a series of psychophysical experiments, described in this paper, studying the perception of real remote (delayed or nondelayed) stiffness. A forced-choice psychophysical protocol was applied, which involved telehaptically probing a set of linear springs. The first experimental study concerned telehaptic discrimination of delayed stiffness. The obtained experimental data were analyzed statistically in three experimental conditions: (1) delayed stimuli with the proposed adaptive impedance telehaptic control active, (2) delayed stiffness with typical direct position/force teleoperation (without adaptive control), and (3) no delay with direct teleoperation. The obtained results, regarding JND values for stiffness, clearly demonstrate that, in the presence of time delay, the proposed adaptive scheme performs significantly better, in terms of human telehaptic perceptual sensitivity, as compared to direct force-reflecting teleoperation. A second experimental study was also conducted, with the object of assessing the performance of the proposed telehaptic control scheme in comparison to a state-of-the-art transparentizing teleoperation method. The experimental analysis focused on comparatively evaluating psychometric transparency, by measuring the differences in PSE values under different time-delay conditions. The results presented and analyzed in the paper demonstrate that the proposed adaptive impedance scheme is significantly more robust to an increase in time delay, ensuring a more reliable telehaptic perception of stiffness.

These results give promising initial indications regarding the benefits that can be anticipated by the application of model-mediated teleoperation strategies, such as the adaptive impedance telehaptic scheme proposed in this paper. Regarding telehaptic perception of simple kinaesthetic features, such as the linear stiffness considered in this work, the proposed adaptive impedance scheme seems to maintain perceptual thresholds close to those reported in the literature for real stimuli (Jones & Hunter, 1990). This experimental finding validates the argument that some of the problems caused by time delays in a telehaptic signal flow can indeed be effectively mitigated by the application of such adaptive control schemes.

Other approaches may also be used to mitigate the effect of time delay, such as potentially training subjects to partially compensate for the delay, for instance, by performing appropriate probing motions. Evaluating the added value of such (user-oriented and not control-oriented) approaches was outside the scope of this work, where our aim was to evaluate the effect of time delay on intuitive perceptual performance; that is, when performing natural probing movements (but within specific limits in terms of probing velocity and maximum induced deformation), in order to systematically assess only the comparative beneficial effect of the proposed adaptive telehaptic control scheme without any other potentially influencing factor.

Further research is planned for the future to perform detailed comparisons between different model-mediated and predictive control schemes, in the context of delayed telehaptic systems, and to provide more thorough validation of experimental findings. Future work will principally follow a twofold direction: (1) to generalize the structure of the adaptive telehaptic controller to cope with more degrees of freedom, dynamic physical characteristics, as well as time and space varying environment properties; and (2) to conduct further experimental (psychophysical) evaluation studies, assessing human telehaptic perception performance for a variety of kinesthetic physical properties, including shape features.

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References

Anderson, R. J., & Spong, M. W. (1992). Asymptotic stability for force reflecting teleoperators. *International Journal of Robotics Research*, *11*(2), 135–149.

Burdea, G. C. (1996). *Force and touch feedback for virtual reality*, 1st ed. New York: Wiley-Interscience.

Burdea, G. C., & Coiffet, P. (2003). *Virtual reality technology*, 2nd ed. New York: Wiley-IEEE Press.

Chang, S.-O., & Okamura, A. M. (2004). Impedance-reflecting teleoperation with a real-time evolving neural network controller. *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2004*, Vol. 3, 2241–2246.

Cortesao, R., Park, J., & Khatib, O. (2006). Real-time adaptive control for haptic telemanipulation with Kalman active observers. *IEEE Transactions on Robotics*, *22*(5), 987–999.

Di Luca, M., Knörlein, B., Ernst, M. O., & Harders, M. (2011). Effects of visual-haptic asynchronies and loading-unloading movements on compliance perception. *Brain Research Bulletin*, *85*(5), 245–259.

Diaz, I., Gil, J. J., & Hulin, T. (2010). Stability boundary and transparency for haptic rendering. In M. H. Zadeh (Ed.), *Advances in haptics* (Chapter 5). Rijeka, Croatia: InTech.

Goethals, P., De Gersem, G., Sette, M., Reynaerts, D., & Van Brussel, H. (2007). Accurate haptic teleoperation on soft tissues through slave friction compensation by impedance reflection. *Proceedings of the Second Joint EuroHaptics Con-*

ference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, WHC'07, 458–463.

Hannaford, B. (1989). A design framework for teleoperators with kinesthetic feedback. *IEEE Transactions on Robotics and Automation*, *5*(4), 426–434.

Hashtrudi-Zaad, K., & Salcudean, S. E. (1996). Adaptive transparent impedance reflecting teleoperation. *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, ICRA'06, pp. 1369–1374.

Hulin, T., Gil, J. J., Sanchez, E., Preusche, C., & Hirzinger, G. (2006). Experimental stability analysis of a haptic system. *Proceedings of the 3rd International Conference on Enactive Interfaces*, 157–158.

Jones, L. A., & Hunter, I. W. (1990). A perceptual analysis of stiffness. *Experimental Brain Research*, *79*(1), 150–156.

Love, L. J., & Book, W. J. (2004). Force reflecting teleoperation with adaptive impedance control. *IEEE Transactions on Systems, Man and Cybernetics, Part B: Cybernetics*, *34*(1), 159–165.

Mitra, P., Gentry, D., & Niemeyer, G. (2007). User perception and preference in model mediated telemanipulation. *Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, WHC'07*, 268–273.

Mitra, P., & Niemeyer, G. (2008). Model-mediated telemanipulation. *The International Journal of Robotics Research*, *27*(2), 253–262.

Mobasser, F., & Hashtrudi-Zaad, K. (2007). Stable impedance reflecting teleoperation with online collision prediction. *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2007*, 476–482.

Mobasser, F., Hashtrudi-Zaad, K., & Salcudean, S. E. (2003). Impedance reflecting rate mode teleoperation. *Proceedings of the 2003 IEEE International Conference on Robotics and Automation, ICRA 2003*, 3296–3302.

Niemeyer, G., & Slotine, J. J. (1991). Stable adaptive teleoperation. *IEEE Journal of Oceanic Engineering*, *16*(1), 152–162.

Nisky, I., Mussa-Ivaldi, F. A., & Karniel, A. (2008). A regression and boundary-crossing-based model for the perception of delayed stiffness. *IEEE Transactions on Haptics*, *1*(2), 73–82.

Nisky, I., Pressman, A., Pugh, C. M., Mussa-Ivaldi, F. A., & Karniel, A. (2011). Perception and action in teleoperated needle insertion. *IEEE Transactions on Haptics*, *4*(3), 155–166.

Passenberg, C., Peer, A., & Buss, M. (2010). Model-mediated teleoperation for multi-operator multi-robot systems. *Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2010*, 4263–4268.

Pressman, A., Nisky, I., Karniel, A., & Mussa-Ivaldi, F. A. (2008). Probing virtual boundaries and the perception of delayed stiffness. *Advanced Robotics*, *22*(1), 119–140.

Shen, X., & Shirmohammadi, S. (2006). Tele-haptics. In B. Furht (Ed.), *Encyclopedia of multimedia*. Berlin: Springer.

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control*. Cambridge, MA: MIT Press.

Slawiñski, E., & Mut, V. (2008). Transparency in time for teleoperation systems. *Proceedings of the 2008 IEEE International Conference on Robotics and Automation, ICRA'08*, 200–205.

Tzafestas, C. S., M'Sirdi, N. K., & Manamani, N. (1997). Adaptive impedance control applied to a pneumatic legged robot. *Journal of Intelligent and Robotic Systems*, *20*, 105–129.

Tzafestas, C. S., Velanas, S., & Fakiridis, G. (2008). Adaptive impedance control in haptic teleoperation to improve transparency under time-delay. *Proceedings of the 2008 IEEE International Conference on Robotics and Automation, ICRA'08*, 212–219.

Velanas, S., & Tzafestas, C. S. (2010). Human telehaptic perception of stiffness using an adaptive impedance reflection bilateral teleoperation control scheme. *Proceedings of the 19th IEEE International Symposium on Robot and Human Interactive Communication*, *RO-MAN 2010*, 21–26.

Vertut, J., & Coiffet, P. (1985). *Teleoperation and robotics—Evolution and development*. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Wang, H., Liu, G. P., Harris, C. J., & Brown, M. (1995). *Advanced adaptive control*. Oxford, UK: Pergamon Press.

Wichmann, F., & Hill, N. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception and Psychophysics*, *63*(8), 1293–1313.

Willaert, B., Goethals, P., Reynaerts, D., Van Brussel, H., & Vander Poorten, E. (2010). Transparent and shaped stiffness reflection for telesurgery. In M. H. Zadeh (Ed.), *Advances in haptics*. Rijeka, Croatia: InTech.

Willaert, B., Vander Poorten, E., Reynaerts, D., & Van Brussel, H. (2008). A pragmatic method for stable stiffness reflection in telesurgery. *Proceedings of the 6th International Conference on Haptics: Perception, Devices and Scenarios, EuroHaptics '08*. Berlin: Springer-Verlag.