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Human Telehaptic Perception of Stiffness using an Adaptive Impedance Reflection Bilateral Teleoperation Control Scheme

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Abstract— **In present days, teleoperation is used in many challenging applications where the tasks to be accomplished from a distance are very complex and require accurate and reliable reproduction of the haptic sensations involved. The main factor that can cause a certain degradation of the quality of teleoperation is the presence of time delays. An effective way of alleviating the consequences of time-delays is the use of an adaptive impedance reflection teleoperation scheme, aiming to reconstruct at the master site a local model of the impedance of the remote environment. The goal of this paper is to show the effectiveness of such a controller via experiments that involve a real remote environment. In these experiments, a forced-choice procedure has been used, where each subject is presented in every trial with two spring fields (remotely located and telehaptically perceived) and is asked to identify the stiffer. The proposed adaptive teleoperation control scheme is compared to a typical direct force-reflection telemanipulation, in the presence of an emulated time delay of 100 msec. Experimental results show the superior performance of the proposed adaptive impedance reflection scheme, which, as opposed to classical direct teleoperation, seems to maintain the thresholds of human haptic perception close to the ones obtained when no time delay is present in the bilateral communication and control loop.**

Index Terms— **Telehaptics, stiffness perception, adaptive impedance control, psychophysics, psychometric curves.**

I. INTRODUCTION

The basic requirements that must be satisfied by any teleoperation system are related to its stability and transparency properties. We call transparency the quality of the reproduction of the haptic sensations involved in carrying out a remote task. This requirement is as important as the stability of the system for the successful completion of the task. It is widely recognized that the presence of time delay in the data transfer between the master and the slave sites can cause severe deterioration of the above mentioned requirements. This problem is mainly due to the distance separating the master from the slave site and limits in information rate and communication bandwidth. Additionally, such delays may be constant but may also be unpredictably varying causing additional difficulties in carrying out the remote task.

In order to cope with the problem of time delay, many methods have been proposed in the literature and are used in various application contexts. Classical control techniques involving the reduction of feedback gains and predictive control schemes (for instance, the Smith predictive control; see [1] for an introduction) have been proposed. In the teleoperation field, some other control schemes have been proposed, based on passivity theory [2] or on adaptive control [4]. All the above 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 needs to be achieved.

In this quest to obtain an optimal trade-off between stability and perceptual performance, an adaptive impedance reflection teleoperation control scheme is used in this paper. The main issue with this type of teleoperation control structure is to achieve fast and stable adaptation of an impedance model capturing the essential physical characteristics of the real remote environment, in order to ensure its accurate and reliable reproduction at the operator site. This control law has already been tested in teleoperation experiments with virtual (simulated) remote environment, and has been proved to exhibit superior performance as compared to a classical direct position-force telemanipulation 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 becomes significant [6].

In the current study, we set out to explore the generality of the above results and extend the experiments to address the effect of the time delay while operating with a real remote environment. Instead of using a virtual (simulated) slave site, the haptic master (PHANTOM® Omni device) is now coupled via network with another haptic device (in this case, a PHANTOM® Desktop™ device) constituting the slave robot that interacts, this time, with a real (remote) physical environment. In a number of recent studies, the human haptic perception of delayed stiffness has been assessed in terms of the PSE values [8][9]. In the work presented in this paper, a series of experiments has been conducted to assess the perceptual performance in terms of the JND values for a human operator manipulating the haptic master and remotely exploring kinaesthetic properties (in our case, linear stiffness) of the remote physical environment. A forced-choice experimental protocol has been employed. The operator sequentially probes two springs at a time and is asked to identify the stiffer. Two types of experiments have been conducted. In the first one, time delay is present and the adaptive impedance controller is involved randomly in half of the trials. In the second experiment, there is no time delay, nor adaptive impedance controller active. The force feedback of the spring field is delayed by 100 ms in relation to the position of the manipulator at the master site. An analysis of the experimental results demonstrates that, in the presence of time delay, the quality of the haptic sensations induced at

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the master site is significantly ameliorated with the use of the adaptive impedance reflection teleoperation controller.

The rest of this paper is organized as follows: Section II describes the theoretical aspects of the proposed teleoperation scheme and the data processing techniques. Section III presents the experimental setup and protocol. Experimental results, as well as data analysis and interpretation are presented in Section IV, and conclusive remarks together with future work directions are given in Section V.

II. THEORETICAL FORMULATION

A. *Adaptive Impedance Reflection Telehaptic Control*

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

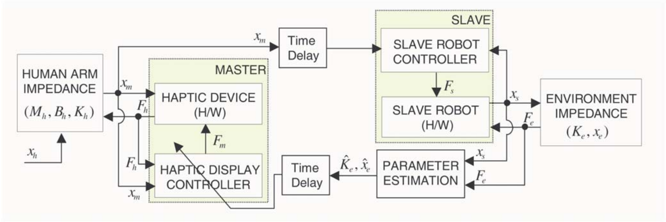

Fig. 1: *Adaptive Impedance Reflection Teleoperation Scheme*

The operator's arm impedance, as shown in Fig. 1, is approximately modelled as a mass-spring-damper system and is 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 sensorimotor system.

The remote environment is described by the following (static) equation:

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

This equation describes the local impedance (in our case, the local stiffness) of the slave robot environment, where K_e is the stiffness of the spring which is probed, x_e is its contact (equilibrium) position, and x_s is the actual position of the end effector of the slave robot.

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 we can estimate the characteristics of the remote environment, K_e and x_e, on-line. These estimations can then be used for the construction of a local model of the remote environment, and particularly for the computation of the force that will be applied on the operator's hand. The goal, thus, of such a controller is to decouple the master and slave systems, enabling the human operator to haptically interact with the continuously adapted local model of the remote environment impedance. The stability of this interaction, in the presence of time delays, depends on the stability properties of the adaptive controller. Our goal is 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.

B. *On-Line Impedance Adaptation Algorithm*

As mentioned in the previous section, the slave robot is in contact interacting with an environment (in our case a spring) with stiffness coefficient K_e and apparent equilibrium position x_e, while the reaction force is computed from equation (2). These characteristics of the remote environment are unknown within the master system; thus, the forces applied to the human operator by the haptic display controller are computed using estimated impedance values, $\hat{K}_e$ and $\hat{x}_e$, according to the following equation:

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

Consequently, the aim of the haptic master controller is to establish a stable interaction between the human operator and the modelled environment, the physical characteristics of which match as closely as possible to the properties of the real remote environment. For this purpose, the proposed adaptive impedance control law provides on-line estimates of the actual remote impedance characteristics, K_e and x_e. The design ojective is to minimize the force estimation error:

$$e_f = \hat{F}_e - F_e \qquad (4)$$

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

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

The adaptation law for the impedance parameters is the following (see [5][6] for the derivation process of the adaptation law and its asymptotic stability proof):

$$\begin{bmatrix} \dot{\hat{K}}_e \\ \dot{\hat{K}}_e \cdot \hat{x}_e + \hat{K}_e \cdot \dot{\hat{x}}_e \end{bmatrix} = -\begin{bmatrix} \gamma_{e1} & 0 \\ 0 & \gamma_{e2} \end{bmatrix} \cdot \begin{bmatrix} -x_s \\ 1 \end{bmatrix} \cdot e_f \qquad (6)$$

where γ_{e1}, γ_{e2} are the adaptation gains ($\gamma_{ei} > 0, i = 1, 2$).

From equation (6) we get:

$$\dot{\hat{K}}_e = \gamma_{e1} \cdot x_s \cdot (\hat{F}_e - F_e) \qquad (7)$$

and

$$\dot{\hat{x}}_e = \frac{(\hat{F}_e - F_e)}{\hat{K}_e} \cdot (-\gamma_{e2} - \gamma_{e1} \cdot x_s \cdot \hat{x}_e) \qquad (8)$$

From equations (7) and (8) on-line updates are computed for the estimates of the remote environment impedance parameters. 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 used to compute the forces applied to the human operator according to Eq. (3).

C. Data Processing Techniques

1) Psychometric curves: 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 [7]. The general form of a psychometric function is:

$$\psi(x, \alpha, \beta, \gamma, \lambda) = \gamma + (1 - \gamma - \lambda) \cdot F(x, \alpha, \beta) \tag{9}$$

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 the points of the curves. Every point on the curve represents the subject's probability to answer "stimulus is stiffer" as a function of the actual difference $\Delta K = K_{stim} - K_{ref}$, where K_{stim} is the stiffness of the stimulus field and K_{ref} is the stiffness of the reference field. This probability was calculated from the following equation:

$$P(\Delta K) = \frac{\sum_{n=1}^{N(\Delta K)} A[n]}{N(\Delta K)}\ ,\ A[n] = \begin{cases} 1 & \textit{stimulus stiffer} \\ 0 & \textit{reference stiffer} \end{cases} \tag{10}$$

where $A[n]$ is a binary representation of the subject's answer, and $N(\Delta K)$ is the total number of trials with the given stiffness difference ΔK. Then, the psignifit toolbox (version 2.5.6 for MATLAB [7]) was used to fit the psychometric curves to the points calculated from equation (10).

2) Just Noticeable Difference (JND): After the fitting of the psychometric curves, the JND values were computed. JND refers to the just noticeable difference between the stiffness levels of two fields. The JND values were calculated for each subject according to the following equation:

$$\mathit{JND} = \frac{F^{-1}(0.75) - F^{-1}(0.25)}{2} \tag{11}$$

The values computed from the above equation provide a quantitative measure of the human haptic perception quality, and were used to compare the effect of the time delay and the use of the controller between different subjects.

III. Experimental Procedures

To validate the proposed adaptive impedance teleoperation scheme we used two experimental evaluation approaches: (a) firstly, we performed a series of probing trials with the time delay present in all of them and the controller active in half of them, and (b) we performed a series of probing trials without time delay and without the use of any adaptive impedance reflection controller (i.e. with direct position-force teleoperation). In both cases the remote environment consisted of a set of four vertically placed springs with different stiffness coefficients, while the time delay was emulated using a buffering algorithm.

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

Fig. 2: *Experimental Setup*

A. Hardware Configuration

The experimental system used to test the adaptive impedance reflection teleoperation control scheme comprises the following four main components (see Figs. 2 and 3):

- *Haptic Interface Device*: A PHANTOM® Omni device was used at the master teleoperation 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.
- *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*: A PHANTOM® Desktop™ haptic device was used as the slave robot. This device can move in three dimensions. It was slightly modified in order 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.

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, in our case 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. Accordingly, the data sent back by the slave comprises the force F_e experienced by the slave robot and its current position. In

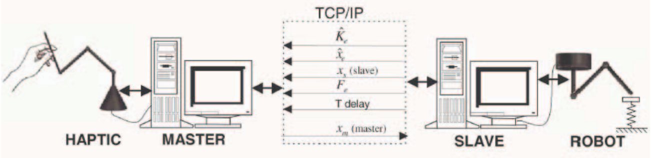

Fig. 3: *Hardware Configuration of the Experimental Setup*

case of an impedance reflection teleoperation control scheme, this data also comprises estimated impedance properties of the remote physical environment.

2) Master Control Interface: Along with the application window that provides the user with information about the current state of the experimental trial, an additional simple graphical user interface was used, visualizing the current haptic device velocity as a colored vertical bar. The length of the bar is proportional to the magnitude of the velocity and its color is green when the magnitude is above a certain limit, otherwise it is red. Graphic display is done using simple (2D) OpenGL commands, and is meant to discourage the user from probing too slow (thus, from artificially reducing the influence of time delay). As a limit we assumed the velocity of 30 mm/sec. In order to avoid probing a spring beyond its physical limit an auditory cue was provided when the maximum allowed level of spring deformation was reached.

B. Experimental Protocol

As mentioned in the previous sections, two series of experiments took place. In both experiments a seated subject held with his/her dominant hand the handle of the PHANTOM Omni haptic device. The subject was watching the monitor of the master controller computer, which provided information about the state of the experiment and the probing velocity. In each trial, subjects were presented with two springs and were asked to choose which of them was stiffer by probing each one of the fields five times at most. Subjects were asked to probe one of the fields first (which was randomly selected by system), then switch to the other (remaining) one by pressing the space button on the keyboard with the free non-probing hand; then, the second field was probed, and 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 was the reference field and had always a stiffness of 117.72 N/m. The other was the stimulus field and its stiffness varied in the different trials between three 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 random. Prior to the test trials, every subject carried out some training trials in order to learn to make rapid movements, keep hand in motion while inside the field, keep probing velocity above the limit and avoid passing the physical limit of the field (minimum working length of the spring) by generating only short movements into it. In each training trial only one spring was probed. The subjects performed 10 training trials before the test trials.

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

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 (with $\gamma_{e1} = 0.1$ and $\gamma_{e2} = 0.1$) and 18 without, in two separate sessions. During these trials, the force feedback of both the stimulus and the reference fields was delayed by 100 ms. In every session each one of the three stimulus fields was presented six times randomly.

2) Stiffness and direct position-force teleoperation: Twenty one subjects participated in this experiment. Each subject performed 18 test trials. During these trials, the force feedback of both the stimulus and the reference fields was not delayed. In every session, each one 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 “ground-truth” non-delayed direct telehaptic perception performance for the bilateral teleoperation experimental system used in this study.

IV. EXPERIMENTAL RESULTS - DISCUSSION

During every session in both experiments the subjects' responses and probing velocities were recorded. All subjects reported that they felt confident about their answers in most of the trials. From the psychometric curves fitted to the responses, we found the JND values for stiffness to be 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), and a JND value of 32 ± 19 N/m (mean Weber fraction: 27%) for the non-delayed trials with direct (no adaptive impedance reflection) control. The difference of the JND value obtained in the first experimental case (time-delay, with adaptive control) from the one obtained in the second case (time-delay, no adaptation) is found to be statistically significant (paired t-test, $t_{18} = -2.3$, two tailed $p = 0.036$), while its slight difference from the JND obtained in the third case is not (two-sample t-test for unequal sample sizes and unequal variances, $t_{37} = 0.25$, two tailed $p = 0.801$). Furthermore, as it could have been anticipated, this increase in the JNDs (implying haptic perception degradation) in the second experimental case (time-delay, no adaptation), with respect to the third experiment (direct non-delayed telehaptic control) is also statistically significant (two-sample t-test for unequal sample sizes and unequal variances, $t_{35} = 0.25$, two tailed $p = 0.022$).

The psychometric curves from the experiments are shown in Fig. 4 and clearly demonstrate that the slope of the fitting sigmoid in the case of the delayed stiffness without adaptive control is decreased as compared to the slope of the curve fitted to trials without delay. This reflects the increasing difficulty to assess the stiffness of a spring in the presence of the reflected force delay. This increase is mainly due to the oscillations observed in most of the trials at the master

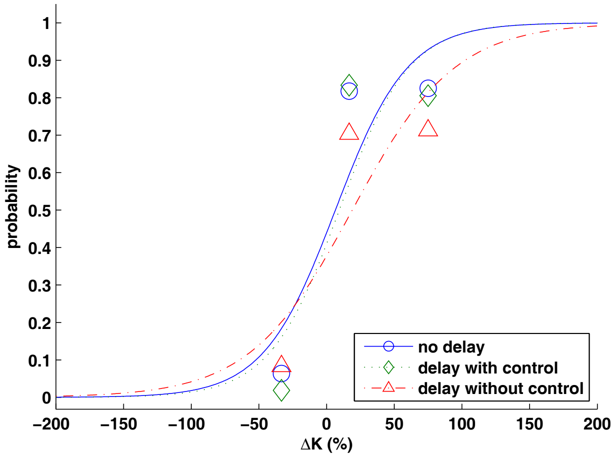

Fig. 4: *Psychometric curves fitted to subjects' answers from all the experimental cases.*

haptic force feedback. The oscillations are a common result of the presence of time delay in the signal flow.

The curve fitted to trials with the presence of the proposed adaptive impedance reflection teleoperation controller seems to nearly coincide with the one obtained in the non-delayed (direct teleoperation) trials. It is reasonable to assume that the best perception of a remote environment is achieved by direct teleoperation when there is no delay in the data transfer between master and slave. Thus, the above finding, in addition to the above results regarding the JND values, clearly shows that the proposed controller has superior performance, with respect to a classical direct position-force teleoperation scheme, in the presence of time delays. The perception achieved by implementing the proposed adaptive impedance teleoperation scheme is very similar to that previously assumed as the best achievable. During the trials including the adaptive controller, no oscillations were observed at the force feedback of the master haptic device, which could be one of the main reasons why the perception was improved.

Table I shows the JND values extracted from psychometric curves fitted to the answers of subjects, from the delayed trials with and without adaptive impedance control, as well as from the non-delayed trials. A subject's JND provides an assessment about his/her uncertainty, namely his/her discrimination ability. In Table I we clearly see that, in the delayed trials with adaptive control, there is a general decrease in the JND values as related to the delayed trials without control. This finding indicates that the discrimination ability of the subjects is clearly improved with the use of the proposed adaptive impedance control scheme (the mean values of the magnitudes of the JNDs are: a) delayed trials with no control: 48 N/m, b) non-delayed trials: 32.3 N/m, c) delayed trials with control: 30.6 N/m).

As already mentioned, in the first series of experiments (comprising the first two experimental cases) the controller was involved randomly in the first or in the second half of the trials. In order to investigate the influence that the order of appearance of the controller had on the perception ability of the subjects, the results (JND values of the delayed trials from Table I) were separated in four groups. These four groups are named as: 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 series of experiments, and 2: 2nd in the experimental series). To see if the differences between groups are significant, we applied ANOVA analysis to our data. We found the p-value between the groups to be 0.0043 which is smaller than 0.05. This result indicates that there are indeed significant differences in the JND values between the groups. To further explore these differences, we applied Tukey's HSD test to the four groups of JNDs. Fig. 5 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 reflection controller is not active. This performance degradation is evident when the subjects begin their trials with the absence of the adaptive impedance controller, but is significantly improved when the proposed teleoperation controller is activated (and this perception performance amelioration surprisingly seems to persist -similarly to a memory or learning effect- even after this controller becomes again inactive, like in the case of Group JND0_2).

TABLE I: *JND values of delayed and non-delayed trials*

Delayed Trials			Non-delayed trials	
	Control	No control		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
			19	2.7981
			20	25.8385
			21	35.8770
$\overline{\lvert x \rvert}$	30.6354	48.0436	$\overline{\lvert x \rvert}$	32.2567

The above results give promising initial indications regard-

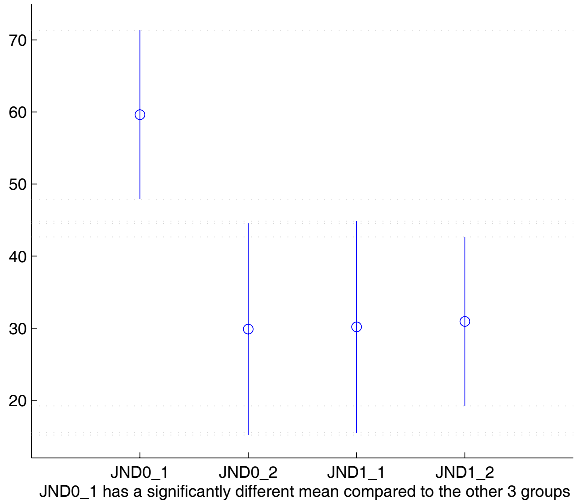

Fig. 5: *Tukey's HSD test for the JND values.*

ing the performance of telehaptic strategies that are based on concepts similar to the proposed adaptive impedance reflection teleoperation control scheme. Regarding telehaptic perception of simple kinaesthetic features, such as the linear stiffness fields used in this work, the presence of a time delay in the network seems indeed to induce a degradation of the human perceptual performance, when classical direct bilateral teleoperation control strategy is followed (as could have probably been anticipated by the degraded transparency reported previously in [6] -in that case, however, for a simulated slave robot). On the contrary, the proposed adaptive impedance telehaptic control scheme seems to maintain the thresholds of perception close to the ones reported in the literature regarding real stiffness perceptual analysis (e.g. [3]), compensating for the time delay in the bilateral communication and control loop.

V. CONCLUSION AND FUTURE WORK

This paper focused on assessing human telehaptic perception of stiffness, using an adaptive impedance reflection teleoperation control scheme to alleviate some of the problems associated with the presence of time delays in the bilateral communication loop. The main issue in such telehaptic control schemes is to achieve fast and stable impedance adaptation, in order to ensure accurate and reliable reproduction of the real remote physical environment characteristics. Online estimation of the remote (slave robot) environment's impedance properties is performed and reflected back to the haptic display controller.

The work presented in this paper aims to assess the effectiveness of the proposed adaptive impedance reflection telehaptic scheme, involving a real remote environment and in the presence of a fixed time delay. The stability and effectiveness of this control scheme with a virtual (simulated) remote environment were assessed in a previous study [6]. In the work presented here, two psychophysical experiments were conducted to assess the effect of time delay and the choice of controller on human telehaptic perception performance. In these experiments, subjects interacted physically (tele-haptically) with springs that were placed at the remote slave site. In the first experiment, the force feedback was delayed (using a buffering algorithm) and the proposed adaptive controller was active in half of the trials. In the second experiment, there was no delay (or at least we did not emulate any delays) while direct position-force data transfer was employed (thus resulting to the "ground-truth" benchmark performance that corresponds to a non-delayed direct teleoperation probing of the remote linear stiffness fields). The psychometric curves derived from the subjects' answers lead to the conclusion that the proposed adaptive impedance telehaptic control scheme clearly alleviates some of the problems associated with the presence of time delay in the bilateral communication and control loop, thus improving the haptic sensations felt by the human operator handling the master haptic device.

These preliminary results give a promising initial indication regarding the performance of the proposed adaptive impedance reflection telehaptic control scheme. As opposed to classical direct force-reflecting teleoperation, the proposed adaptive control scheme seems, indeed, to maintain the thresholds of perception close to the ones reported in the literature (for real stiffness perception), compensating for the time delay in the bilateral communication and control loop. 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 properties, as well as (iii) time and space varying environment properties; and (b) to conduct further experimental (psychophysical) evaluation studies, assessing human *telehaptic perception* performance, with respect to various kinaesthetic physical properties, including shape features.

REFERENCES

[1] H. Wang, G.P. Liu, C.J. Harris and M. Brown, *Advanced Adaptive Control*, Pergamon Press 1995.

[2] R. J. Anderson, and M. W. Spong, "Asymptotic Stability for Force Reflecting Teleoperators", *Intern. Journal of Robotics Research*, vol. 11, no. 2, pp.135-149, 1992.

[3] L. A. Jones and I. W. Hunter, "A perceptual analysis of stiffness" *Exp. Brain Res.*, Vol.79, pp.150-156, 1990.

[4] G. Niemeyer, and J. J. Slotine, "Stable Adaptive Teleoperation", *IEEE Journal of Oceanic Engineering*, vol. 16, no.1, pp.152-162, 1991.

[5] C. S. Tzafestas, N. K. M'Sirdi and N. Manamani, "Adaptive Impedance Control Applied to a Pneumatic Legged Robot", *Journal of Intelligent and Robotic systems*, 20: 105-129, 1997.

[6] C. S. Tzafestas, S. V. Velanas and G. Fakiridis, "Adaptive Impedance Control in Haptic Teleoperation to Improve Transparency under Time-Delay", in Proceedings of the *2008 IEEE International Conference on Robotics and Automation (ICRA'08)*, Pasadena, California, May 19-23, 2008.

[7] F. Wichmann and N. Hill, "The Psychometric Function: I. Fitting, Sampling, and Goodness of Fit", *Perception and Psychophysics*, vol. 63, pp. 1293-1313, 2001.

[8] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "A Regression and Boundary-Crossing-Based Model for the Perception of Delayed Stifness", *IEEE Transactions on Haptics*, 1: 73-82 (2008).

[9] A. Pressman, I. Nisky, A. Karniel, and F. A. Mussa-Ivaldi, "Probing Virtual Boundaries and the Perception of Delayed Stiffness", *Advanced Robotics*, vol. 22, no. 1, pp. 119-140, 2008.