2012 IEEE RO-MAN: The 21st IEEE International Symposium on
Robot and Human Interactive Communication.
September 9-13, 2012. Paris, France.

Model-Mediated Telehaptic Perception of Delayed Curvature

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Abstract— **This paper proposes a model-mediated telemanipulation scheme, focusing on the kinaesthetic perception of specific geometric properties of the remote environment in the presence of time delay. The basic idea is inspired from previous work on impedance-reflection teleoperation, which is here extended to incorporate the construction of a two-dimensional local geometric model. This model incorporates the local curvature of the remote environment, estimated on-line using a recursive least squares (RLS) method, which is then used to reconstruct a virtual surface model at the master site for haptic display. A series of experiments has been conducted, where each subject manipulated the haptic master to kinaesthetically explore the surface of a remote (virtual) environment. The analysis of the obtained experimental results, in terms of telehaptic discrimination of curvature, shows the effectiveness of the proposed model-mediated scheme at mitigating some of the adverse effects of time delay in the communication loop.**

I. INTRODUCTION

Bilateral telemanipulation offers the ability for a human user to manipulate a distant robotic device and interact with a remote environment. Most telemanipulation tasks include physical contact with the remote environment, involving not only motion control of the slave robotic device but also the application of forces at the remote site. In order for this interactive manipulation to be successful, some kind of reliable perception of the remote environment's physical properties needs to be established, in addition to ensuring accurate and fast response to the requested actions performed by the human operator. Thus, in such tasks, an efficient haptic user interface has to be implemented in order to enable the user to issue appropriate motion and force control commands, as well as to perceive the characteristics of the interaction taking place at the slave site.

In such systems, which are based on force and motion exchange, one of the most frequent and difficult problems is the presence of substantial communication delays. Even the presence of a time delay of some tens of milliseconds can significantly deteriorate the stability and performance of a bilateral telemanipulation system. This delay causes a lag in feedback which in turn degrades the user's perceptions while delayed commands make the manipulation difficult and sometimes impossible.

Many approaches have been proposed in the literature in order to cope with this problem. The form and implementation of information interchange depends on the nature of the remote environment and the level of the communication delay between the master and the slave site. In situations where time delay is very small or not present at all, direct communication of position and force signals can be used (this approach generalized in four-channel systems is presented in [1]). When telemanipulating over small to medium delays (i.e. tens to hundreds of milliseconds) direct communication becomes impractical and unstable. In such cases, advanced controllers have been proposed, based on maintaining passivity under delay [2], wave variable encoding of the force and motion information [3]-[5], or model-mediated approaches [6], including adaptive control [7] and adaptive impedance reflection schemes [8]. For larger delays in the communication channel, the force-motion feedback approach can be replaced by more abstract control algorithms, in which greater autonomy is passed on to the slave robot [9]-[11]. For extremely large delays and great environment uncertainty, supervisory control methods can be applied, where the slave robot operates almost entirely autonomously with only high-level task instructions sent at sparse time intervals [12], [13].

In this paper, we extend previous work by proposing a model-mediated telemanipulation scheme focusing on specific geometric properties of the remote environment, targeted at systems with delays of some hundreds of milliseconds. The basic idea is similar to the one proposed in [8], that is, the on-line construction of a local model of the remote environment at the haptic master site. The difference is that the model now concerns the local 2D curvature of the remote environment, which is estimated on-line using a recursive least squares (RLS) method. This method, despite its simplicity, is proved to be very effective at improving performance when considerable time delay is present in the bilateral teleoperation loop.

In the work presented in this paper, a series of experiments is conducted in order to assess the effectiveness of the proposed method by exploring the telehaptic perception of curvature under time delay. Human observers are exposed to shape stimuli that deliver zeroth- and first-order shape information, that is position and slope, which have been proved to be more than sufficient for curvature discrimination (see [17]). At the master haptic user interface, a PHANTOM® Omni device is used, which is remotely coupled to a virtual robot manipulator (in the form of a spherical probe) interacting with a virtual cylindrical surface (of variable radius and 2D positioning) that constitutes the remote environment. In our experiments, telehaptic curvature discrimination performance is evaluated in terms of the just-noticeable difference (JND) values for a human operator manipulating the haptic master and kinaesthetically exploring the surface of the remote (virtual) environment. A forced-choice experimental protocol has been employed, with two

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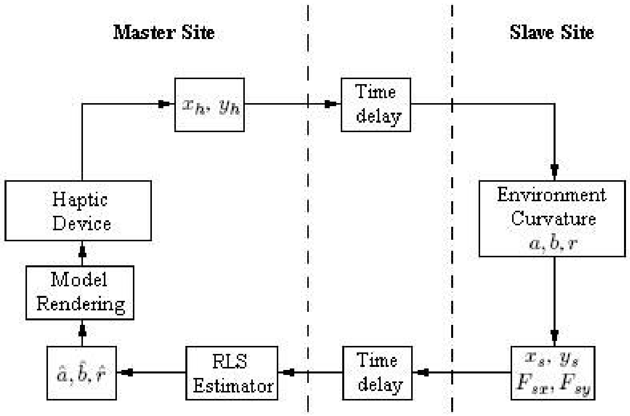


Fig. 1: *Model-mediated (curvature reconstruction) teleoperation scheme (x_h, y_h: coordinates of the haptic handle tip)*

experimental conditions assessed in comparison (involved randomly in the user trials): (i) direct (position/force) telemanipulation control with no time delay vs. (ii) model-mediated telemanipulation (using the proposed RLS-based curvature estimator) with constant round-trip time delay (set to 100 ms, in these experiments). The analysis of the experimental results presented in this paper shows that the telehaptic curvature discrimination performance achieved at the master site when applying the proposed model-estimation scheme, despite the presence of considerable time delay, is comparable to the results obtained in the ideal non-delayed direct telemanipulation condition. This experimental finding demonstrates the effectiveness of the proposed model-mediated scheme in mitigating some of the adverse effects of time delay in the bilateral telemanipulation loop.

The 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 research directions are given in Section V.

II. THEORETICAL FORMULATION

A. *Recursive Least Squares Bilateral Teleoperation Scheme*

Fig. 1 shows the overall block diagram of the model-mediated (curvature reconstruction) haptic teleoperation scheme. The human operator, as shown in Fig. 1, interacts with a local model of the remote environment, which is reconstructed at the master site. The motion and force commands of the operator are transmitted over time delay to the slave site. The forces exerted from the interaction with the remote environment as well as the position of the end effector of the slave robot are transmitted over time delay back to the master site, where they are utilized by a recursive least-squares (RLS) estimator in order to update the local model of the remote environment. The recursive equations used by the RLS estimator are the following (see [14] for the derivation of these equations):

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)(z(t) - \phi^T(t)\hat{\theta}(t-1)) \tag{1}$$

$$K(t) = P(t)\phi(t) = P(t-1)\phi(t)(\lambda I + \phi^T(t)P(t-1)\phi(t))^{-1} \tag{2}$$

$$P(t) = (I - K(t)\phi^T(t))P(t-1)/\lambda \tag{3}$$

where θ is the vector of the model parameters to be estimated, $\hat{\theta}$ is the estimate of θ, ϕ denotes the regression matrix, λ refers to the forgetting factor, and z is the observation vector, which is generally described by the following equation:

$$z(t) = \phi^T(t)\theta \tag{4}$$

The estimate $\hat{z}$ is given by a similar equation:

$$\hat{z}(t) = \phi^T(t)\hat{\theta} \tag{5}$$

If we assume that the remote environment consists of a circular curve, then it can be described by the following geometrical model:

$$x_a = a + r\cos\omega \tag{6}$$

$$y_a = b + r\sin\omega \tag{7}$$

where x_a, y_a are the coordinates of a point on the curve, a, b are the coordinates of the center of the circle, r is the radius of the circle, and ω is the angle formed between the x-axis and the ray connecting (a, b) to (x_a, y_a).

From equations (4), (6) and (7) we obtain for the regression matrix:

$$\phi^{\mathrm{T}}(t) = \begin{bmatrix} 1 & 0 & \cos\omega(t) \\ 0 & 1 & \sin\omega(t) \end{bmatrix} \tag{8}$$

$$\theta = \begin{bmatrix} a & b & r \end{bmatrix}^{\mathrm{T}} \tag{9}$$

As mentioned above, the slave robot interacts with a circular curve, the geometric attributes of which (namely its radius r and the coordinates a, b of its center) are unknown within the master site; thus, the forces applied to the human operator by the haptic display controller are computed using the estimated values of these geometric characteristics, namely $\hat{r}$, $\hat{a}$ and $\hat{b}$. These estimated values are computed as follows. The RLS estimator computes the values of the components of vector $\hat{\theta}$ by recursively executing equations (2), (1) and (3) until they converge to the real values of the geometric model. The convergence is achieved when the difference between $z(t)$ and $\hat{z}(t)$ is minimized.

To make the execution of the estimator possible, the coordinates of the slave robot end-effector (namely x_s, y_s) as well as the forces exerted from its interaction with the remote environment (namely F_{sx}, F_{sy}) are considered known during every recursion. The coordinates x_s, y_s are considered as the real values of $z(t)$ while the forces are used for the calculation of the angle ω:

$$\omega = \mathit{atan2}(F_{sx}, F_{sy}) \tag{10}$$

where $\mathit{atan2}(x, y)$ is the arctan of y/x which takes into consideration the signs of x, y in order to determine the quadrant in which the angle resides.

For t = 0 we need to initialize some parameters in order to start executing the RLS estimator. These parameters are $\hat{\theta}(t)$, $P(t)$, $z(t)$ and $\phi(t)$. We assume:

$$\hat{\theta}(0) = P(0)\phi(0)z(0) \tag{11}$$

$$P(0) = (\phi(0)\phi^{\mathrm{T}}(0))^{-1} \tag{12}$$

if $\phi(0)\phi^{\mathrm{T}}(0)$ is nonsingular, else:

$$P(0) = \delta^{-1} I \tag{13}$$

$$z(0) = \left[\begin{array}{c} x_s(0) \\ y_s(0) \end{array} \right] \tag{14}$$

$$\phi^{\mathrm{T}}(0) = \left[\begin{array}{ccc} 1 & 0 & \cos\omega(0) \\ 0 & 1 & \sin\omega(0) \end{array} \right] \tag{15}$$

After every recursion a set of the estimates $\hat{a}$, $\hat{b}$ and $\hat{r}$ is available. This triplet constitutes the on-line update for the estimates of the remote environment geometric parameters. These estimates are then reflected back to the haptic display controller at the master site, as shown in Fig. 1, and are used to compute the forces applied to the human operator.

B. Data Processing Techniques

1) Psychometric curves: The task of comparing two curves by exploring them is a psychophysical discrimination task. A common method of quantifying 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 [15]. The general form of a psychometric function is the following:

$$\psi(x, \alpha, \beta, \gamma, \lambda) = \gamma + (1 - \gamma - \lambda) \cdot F(x, \alpha, \beta) \tag{16}$$

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

We derived the psychometric functions by, firstly, estimating the points of the psychometric curves. Every point is the subject's probability to answer "stimulus is more convex" (i.e. it has a smaller radius of curvature) as a function of the actual difference $\Delta R = R_{comp} - R_{ref}$, where R_{ref} is the radius of the reference circular curve (reference stimulus) and R_{comp} is the radius of the comparison circular curve (comparison stimulus). This probability was calculated by the following equation:

$$P(\Delta R) = \frac{\sum\limits_{n=1}^{N(\Delta R)} A[n]}{N(\Delta R)}, \; A[n] = \left\{ \begin{array}{ll} 1 & \textit{comparison more convex} \\ 0 & \textit{reference more convex} \end{array} \right. \tag{17}$$

where $A[n]$ is a binary representation of the subject's answer, and $N(\Delta R)$ is the total number of trials with the given radius difference ΔR. The *psignifit* toolbox (version 2.5.6) for MATLAB [15] was then used to fit the psychometric curves to the points calculated from equation (17).

2) Point of Subjective Equality (PSE) and Just Noticeable Difference (JND): After the fitting of the psychometric curves, the PSE and JND values were computed. The PSE value in this case indicates the radius difference that is perceived as zero. When a subject is unable to discriminate between two curvatures, the probability to answer that the comparison stimulus is more convex is theoretically 0.5. Thus, assuming that F describes the psychophysical mechanism of decision, the PSE value is calculated according to:

$$\mathit{PSE} = F^{-1}(0.5) \tag{18}$$

We expect to observe a zero PSE value on the psychometric curves derived both for the non-delayed trials and for the delayed trials with the application of the RLS estimator. In case that the whole psychometric curve appears shifted, a positive PSE value would imply underestimation of the perceived comparison stimulus (since this situation corresponds to two curves being perceived as identical when the actual difference between their radii is positive) and similarly, a negative PSE value would imply overestimation of perceived comparison stimulus (radius).

Regarding now the JND (just noticeable difference) between the radii of two circular curves, its value was calculated according to the following equation:

$$\mathit{JND} = \frac{F^{-1}(0.75) - F^{-1}(0.25)}{2} \tag{19}$$

The values computed from the above equation were used to assess the effect of the time delay and the performance of the model estimation scheme in terms of the curvature discrimination ability for different subjects.

III. EXPERIMENTAL PROCEDURES

The effectiveness of the proposed model-mediated teleoperation scheme was evaluated experimentally by performing a series of telehaptic exploration trials. Two experimental conditions were assessed in comparison: (i) the first one, involving a (constant) time delay and applying the proposed RLS estimator, and (ii) the second one, applying a typical direct force-reflecting teleoperation scheme, without any time delay. Each experimental condition was applied randomly in half of the trials. The remote (virtual) environment at each exploration task consisted of a circular arc (in fact, a patch of a virtual cylindrical surface, as shown in Fig. 3), while the time delay (when present) was emulated using a buffering algorithm.

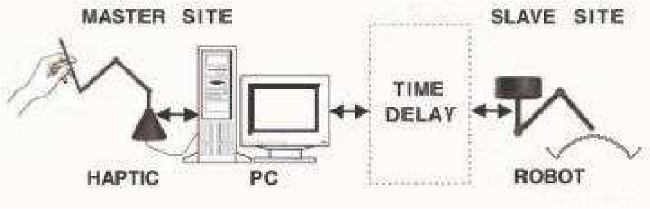


Fig. 2: *Experimental Setup*

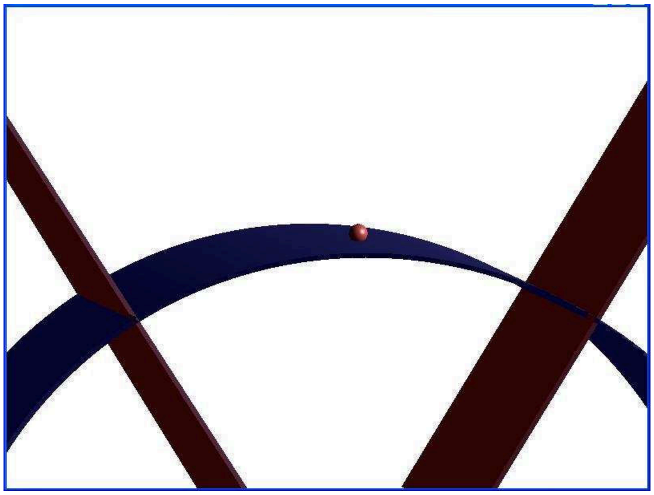


Fig. 3: *Virtual Remote Environment*

A. Hardware Configuration

The experimental system used to test the proposed teleoperation scheme comprised the following components (see Fig. 2):

- Haptic Interface 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 axes. The device communicates with the master computer via a FireWire (IEEE 1394) port, and its controller operates at a maximum sampling frequency of 1 kHz.
- Master/Slave Controller Computer: In this experiment, a single computer was used to perform all operations related to the computation of feedback forces based on the local curvature model, communication and control of the haptic interface device, as well as control of the simulated (virtual) slave environment and execution of the buffering algorithm to emulate time-delay when necessary. The RLS estimator operated in a separate thread at a sampling rate that was approximately equal to 1.2 kHz.

B. Experimental Protocol

During the experiments, a seated blindfolded subject held with his/her dominant hand the handle of the PHANTOM® Omni haptic device. A forced-choice psychophysical method was employed in the experimental protocol. In each trial, the subject was presented consecutively with a pair of stimuli (circular regions - curvatures) and was asked to choose which of them felt more convex (i.e. had a smaller radius or, equivalently, a higher curvature) by haptically exploring each one of them for a maximum time period of 20 seconds. The subjects were instructed to always keep the virtual probe in contact with the surface during the haptic exploration phase. When the exploration period was exceeded, an auditory cue sounded in order to discourage the users from continuing to explore the same curve and to provide a reminder for proceeding to the next stimulus. The subjects were asked to haptically explore one of the curves first (which was randomly selected by the system), then switch to the other (remaining) one by pressing the white button on the handle of the Omni device; then the second curve was explored, and once the users felt confident about their answer they switched to the answer mode by pressing the same button as before. The subjects were then asked to state their answer (i.e. which curve felt more convex) and the answer was inserted to the system by the supervisor of the experiment. In the case that subjects did not feel confident about their answer after exploring the second curve, they were allowed to go back to the previous phase and explore the curves again, by pressing a virtual button, using the tip of the Omni handle, located above the curves at an appropriate distance. Subjects were allowed to do that as many times as they needed.

In each trial, one of the displayed circular arcs always was the reference stimulus, which had a fixed radius of curvature equal to 90 mm. The other was the comparison stimulus and its radius of curvature was selected among three smaller and three larger sizes, respectively: 70%, 80%, 90%, and 110%, 120%, 130% of the reference curvature radius. Both curves had the same length (100 mm) and subjects were not allowed to explore them beyond their limits. This was achieved by displaying, at these limits, a pair of virtual walls perpendicular to the curves (as shown in Fig. 3). Moreover, in every trial, the position of the topmost points of the two explored curves varied randomly between 0 and 5 mm (to compensate for any position memorization effect in the psychophysical experiments). Each pair of reference and comparison curvature stimuli was considered as a single test trial. The order of appearance of these two curvatures in each trial was random. Prior to the test trials, every subject carried out a set of training trials in order to get familiarized with the experimental setup. In each training trial, a pair of reference and comparison curvatures was presented, chosen randomly among all possible pairs. The subjects performed 10 training trials before the actual test trials.

The experiment conducted was thus organized as follows. Twenty subjects participated in the experiment. Three of them were left-handed. Each subject was presented, in random order, with all possible combinations of reference and comparison curvatures, six times for each pair of stimuli (three times in each one of the two experimental conditions); that is, every subject performed: (i) 18 test trials with time delay (in this experiment, set to 100 ms) and with the RLS estimator active ($\delta = 10^{-6}$, $\lambda = 0.99$ before convergence, $\lambda = 1.0$ after convergence) present, and (ii) another 18 test trials in direct teleoperation mode (no RLS estimator) and no time delay in the force-position signal flow.

IV. EXPERIMENTAL RESULTS - DISCUSSION

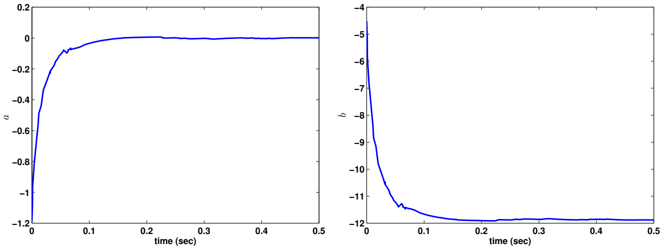
A. *Curvature Estimator Convergence*

We first evaluated the convergence properties of the RLS estimator in the proposed model-mediated telehaptic perception scheme. Fig. 4 shows the convergence of the elements of parameter estimate vector $\hat{\theta}$, along with the time evolution of the whole estimated curve for a typical exploration task, with time delay and RLS estimator present, and with a relatively low exploring velocity ($< 0.01 m/s$). From Figs. 4a - 4c we can clearly see that the geometric parameters of the estimated curve converge to their nominal values within approximately 200 ms, which is a satisfying convergence time (note, in these figures, that the time $t = 0$ corresponds to the first time instant where an RLS estimate is obtained and not to the beginning of the experiment). The convergence is fairly smooth and is accomplished without disturbing oscillations. Fig. 4d shows that the estimated curve smoothly converges to the nominal one with an increasing estimated radius of curvature. In the same figure, the directions of the displayed forces are also depicted as computed by the model-mediated scheme (by means of the haptic master probe in contact with the reconstructed virtual curvature).

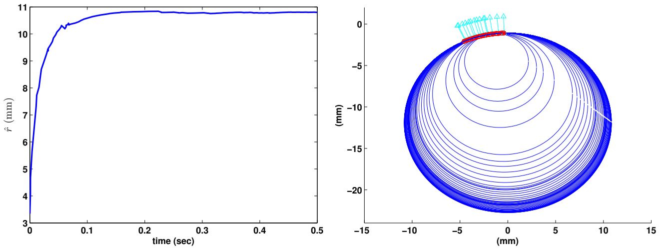
Fig. 5 shows the evolution of the direction (orientation angle) of the displayed force vector (solid line), for the first 200 ms of the curvature haptic exploration time period, in relation to the orientation angle of the haptic probe position vector (in cylindrical coordinates, with the center of the reference frame located on the primary axis of the actual cylindrical shape being explored). The dashed line represents the ideal force/position relation regarding the change of the force direction (force vector orientation angle) during haptic exploration. From this figure we can observe that, during a small period of time, the haptic operator is in fact presented with a slightly distorted version of the remote curved shape, which is caused by the difference between the direction of the displayed force vector and the actual position of the haptic probe on the explored surface (the reflected force direction angle is in fact slightly larger than the real one, because the initial curvature is overestimated before progressively converging to the real one). This force/position discrepancy may create some sort of haptic illusion, which however lasts only some tens of milliseconds and is not expected to affect the haptic perception performance, as is evaluated in the following paragraph.

B. *Telehaptic Perception Results - Curvature Discrimination*

In this paragraph, the effectiveness of the proposed model-mediated teleoperation scheme is experimentally evaluated in terms of the JND values for perceived curvature, with human subjects kinaesthetically exploring a remote (virtual) curved shape via the haptic interface, following the experimental protocol described in Section III-B. During these experiments, the responses of all the subjects were recorded. All subjects reported that they felt confident about their answers in most of the trials. The psychometric curves fitted to all accumulated subjects' responses are shown in Fig. 6. This figure clearly demonstrates that the psychometric curve fitted to the delayed trials that involve the proposed RLS estimator nearly coincides with the one corresponding to the non-delayed direct teleoperation trials. The experimental condition of direct non-delayed data transfer between the master and the slave sites corresponds, in fact, to an ideal (best achievable) perception of the remote environment during a telemanipulation task, thus constituting a type of benchmark system performance. Therefore, we can conclude that the proposed model-mediated scheme, based on the RLS curvature estimation algorithm, manages to mitigate some of the adverse effects of time delay, achieving a telehaptic perception performance for curvature that is very similar to the ideal (non-delayed) one assumed as the best achievable.



(a) *Parameter $\hat{a}$ vs time* (b) *Parameter $\hat{b}$ vs time*



(c) *Parameter $\hat{r}$ vs time* (d) *Estimated curve evolution*

Fig. 4: *Curvature estimator convergence.*

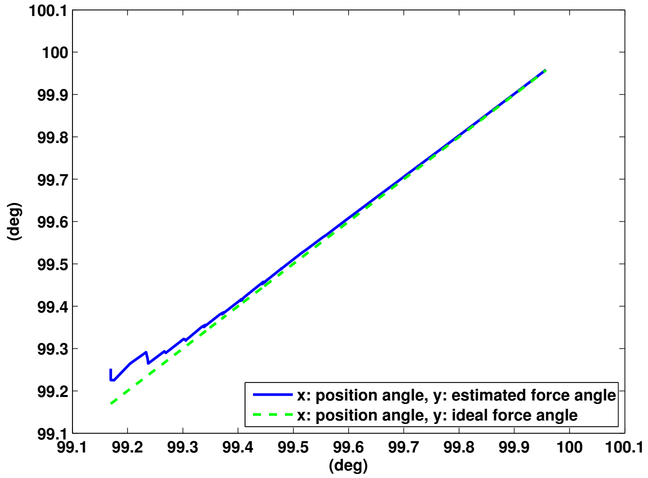


Fig. 5: *Haptic force direction vs position orientation angles.*

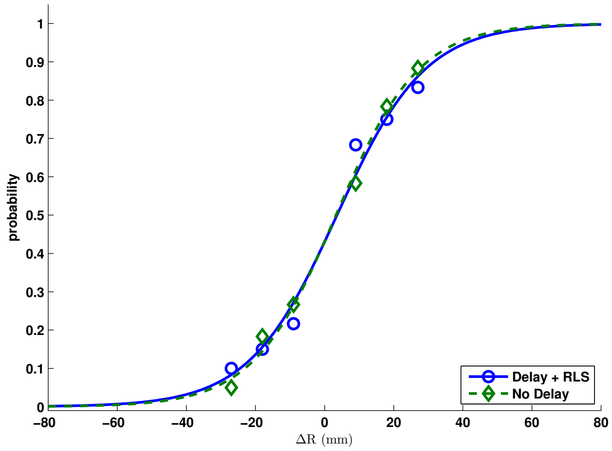


Fig. 6: *Psychometric curves fitted to all subjects' responses.*

TABLE I: *Percentages of correct answers*

	RLS + Delay	*No Delay*
$\frac{R_{comparison}}{R_{reference}}$	correct answers (%)	
0.70	90	95
0.80	85	81.67
0.90	78.33	73.33
1.10	68.33	58.33
1.20	75	78.33
1.30	83.33	88.33
JND (mm)	14.0391	13.2043
Weber fraction	0.1560	0.1467
PSE (mm)	3.5859	3.3112

Table I shows the percentages of accumulated correct answers for all the subjects along with the JND and the PSE values obtained from the psychometric curves fitted to their responses. We found the JND for curvature (radius R) discrimination to be 14.0391 mm (weber fraction: 0.1560) for the delayed trials with the estimator present, and 13.2043 mm (weber fraction: 0.1467) for the non-delayed (direct teleoperation) trials. The above finding, in addition to the outcome on the fitted psychometric curves presented above, supports our conclusion concerning the effectiveness of the proposed model mediated scheme. Concerning now the PSE, it was found to consistently have positive (though relatively small) values (3.5859 mm for the delayed trials and, similarly, 3.3112 mm for the non-delayed ones) indicating that there is a slight underestimation of the radius of the perceived curves (or overestimation of the perceived curvature; meaning that subjects seemed more confident in discerning differences between the reference stimulus and the comparison stimuli of smaller radii, i.e. of higher curvature, while the stimuli of lower curvature in this experiment were more difficult to discriminate). The above findings are consistent with the results reported in [16], where Weber fractions ranged between 0.084 and 0.143 for various radii, and the psychometric curves fitted to subjects' responses indicated a small underestimation of the perceived curves.

TABLE II: *PSE and JND values of delayed and non-delayed trials*

	RLS + Delay		No Delay	
Subject	*PSE*	*JND*	*PSE*	*JND*
1	-0.2632	0.3702	8.2491	1.1724
2	-0.2632	0.3702	9.4282	0.6794
3	4.3164	9.6306	8.2491	1.1724
4	-0.0000	50.7962	33.8733	25.9019
5	20.4410	28.5929	8.6210	39.5757
6	10.2024	18.9298	-0.0000	23.6305
7	-0.2632	0.3702	-4.4575	7.9438
8	10.2024	18.9298	-9.0018	14.0442
9	-5.2194	20.0464	9.4282	0.6794
10	58.5025	91.4977	25.4566	25.1234
11	8.2491	1.1724	0.6483	0.6344
12	-0.2632	0.3702	-0.2632	0.3702
13	8.2491	1.1724	-9.3284	0.5199
14	-0.0000	17.7509	9.1693	5.9957
15	8.2491	1.1724	-0.0000	15.4838
16	8.6210	39.5757	10.6415	50.1266
17	14.0533	67.5069	4.4113	13.1405
18	-0.3565	0.5740	-4.5899	15.1332
19	9.1693	5.9957	4.3164	9.6306
20	-0.2632	0.3702	0.6483	0.6344
$\overline{\lvert x \rvert}$	7.6682	18.7598	5.2750	12.5796
σ	13.1888	24.9218	10.1795	13.8019

Table II shows the PSE and JND values computed from psychometric curves fitted to answers of every individual subject separately, for the experimental conditions. From the computed PSE values we can conclude that the subjects demonstrated similar behavior during the delayed and non-delayed trials (the mean values for the PSE are: a) delayed trials with RLS estimator: 7.6682 mm, b) non-delayed trials: 5.2750 mm). The fact that these two mean PSE values are positive denotes once again that subjects tend to underestimate the radius of the explored remote curve. However, these values are relatively small with respect to the various values of the radii appeared in the experiments. By observing now the JND values, similar conclusions can be drawn. JND provides an assessment about a subject's discrimination ability. In the delayed trials there is a small increase in the JND values as compared to the non-delayed trials (the mean values for the JND are: a) delayed trials with RLS estimator: 18.7598 mm, b) non-delayed trials: 12.5796 mm). This finding indicates that the discrimination ability of the subjects in the delayed trials is slightly deteriorated as compared to the one achieved in the non-delayed trials. However, the differences between the JND values obtained in the two experimental conditions are found to be statistically not significant (two-sample t-test, $t_{38} = 0.9456$, two tailed $p = 0.3503$, significance level 5%). The above experimental findings thus validate our conclusion that the proposed model-mediated scheme is very effective at compensating efficiently for the presence of time delay in the telehaptic control loop.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a model-mediated telemanipulation scheme to improve telehaptic perception of specific local geometric properties of a remote environment under time-delay. The basic idea is based on performing an online RLS estimation of the local curvature of the remote environment, which is then used to reconstruct a model of the telehaptically explored curved shape. The effectiveness of the proposed method was evaluated experimentally in a bilateral haptic teleoperation task, involving a set of virtual remote surfaces in the presence of time delay. We carried out a series of psychophysical experiments to evaluate the effect of time delay and the application of the proposed RLS model reconstruction scheme on human telehaptic perception performance. In these experiments, subjects haptically explored the surface of a simulated (virtual) remote environment, which consisted of a cylindrical area of varying curvature. Two experimental conditions were assessed in comparison: a) in half of the trials, the data transfer between the master and the slave site was delayed (using a buffering algorithm, imposing a fixed 100 ms time delay) with the proposed estimator active, while b) in the rest of the trials, there was no time delay and a direct position-force data transfer was applied (thus corresponding to a benchmark system performance). The obtained experimental results demonstrate that the convergence properties of the proposed curvature estimator are very satisfactory, introducing very slight distortions in terms of the force/position relation displayed to the human subject. The psychometric results obtained confirm this conclusion, showing that the discrimination ability for curvature obtained when applying the proposed model-mediated scheme in the presence of a fixed (100 ms) time delay (which would have normally completely destabilized a typical teleoperator) is now very similar to the haptic perception performance achieved when a direct force-reflecting teleoperation scheme is applied in the absence of any delay (which sets the benchmark for this experimental setup).

A statistical analysis of the results validates our conclusion, demonstrating that model-mediated schemes can be efficiently used to mitigate some of the adverse effects of time delay in the communication loop and to improve telehaptic exploration performance in tasks that may be more complex than simple 1D stiffness/impedance reflection (as was previously reported in the literature), involving higher dimensional and space or time varying kinaesthetic properties. Future work will focus on extending model-mediated haptic teleoperation schemes to address tasks that involve shape reconstruction and continuous estimation of geometric attributes in three dimensions, also incorporating dynamic kinaesthetic and/or tactile properties.

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