

Dynamic Model Displacement for Model-mediated Teleoperation

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ABSTRACT

In this paper, we study and extend the concept of model-mediated teleoperation (MMT) for teleaction systems which provide live video feedback from the remote side with a time delay. In MMT, the haptic feedback is rendered locally on the operator side using a simple object surface model in order to keep the haptic control loop stable in the presence of communication delays. Because the live video from the remote side is received with delay, this results in a visual-haptic asynchrony for the displayed interaction events. In addition, sudden model parameter updates can lead to “model-jump” effects for the displayed haptic feedback. Both effects degrade the user experience and system performance. To address these issues, we propose an extension of MMT which we call model-displaced teleoperation (MDT) in this paper. In MDT, we adaptively shift the position of the local surface model to delay the haptic contact with the environment, thus compensating the visual-haptic asynchrony and avoiding the model-jump effect. As the haptic feedback is still rendered locally, the advantages of the MMT approach are retained and instabilities in the haptic interaction are avoided. In our experiments, we determine the optimal displacement compromise between visual-haptic asynchrony, the model-jump effect and perceived distance errors. Moreover, the subjective experience and objective task performance of the proposed MDT and the original MMT for a teleoperation setup with soft objects are evaluated. Our results show that the users prefer the MDT method compared to MMT once the communication delay between the teleoperator and the operator exceeds 50ms. In addition, the task error rate is reduced by about 50% and the subjects are better able to control their contact force for system delays larger than 50ms if the MDT method is employed.

Index Terms: model-mediated teleoperation, asynchrony compensation, model-jump effect, model displacement

1 INTRODUCTION

A telepresence and teleaction (TPTA) system consists of three main parts: the human operator (OP)/master system, the teleoperator (TOP)/slave system, and the communication link/network in between [1]. The TOP is typically controlled by position or velocity commands generated by the OP and returns the haptic and visual signals sensed during its interaction with the remote environment back to the OP. The commands and the visual-haptic data are exchanged over a communication network. On the operator side the haptic and visual feedback signals are displayed to the user, which allows the users to haptically and visually immerse themselves in the remote environment.

For teleoperation systems with geographically separated operators and teleoperators, time delay introduced by the communication network always exists. It is well known that even a small time de-

lay in the haptic channel jeopardizes the system stability and performance [2]. Several control architectures have been developed to enable a stable TPTA system in the presence of communication delays. In [3, 4], the concept of model-mediated teleoperation (MMT) is proposed, which guarantees a stable TPTA system by local rendering of the haptic feedback using a simple object surface (e.g. a plane). Sudden model updates occur when new environment parameters (position and impedance) are detected at the TOP and signaled to the OP, which leads to disturbing “model-jump” effects [5]. In [5], a haptic rendering method is proposed to attenuate the model-jump effect for position change of rigid objects. However, for non-rigid environments, the model-jump effect for impedance change (stiffness, friction, etc.) persists. In addition, due to the negligible delay of the locally rendered haptic feedback, the asynchrony between the displayed haptic signals and the video feedback received from the remote side grows with increasing communication delay [3].

The effect of delay on human task performance has been investigated in many studies [6-8]. For example, in [6], the effect of the visual-feedback delay on the user’s task completion time is examined. It is shown that the performance is affected for delays exceeding 75 ms. In [7], the consequence of time delay on visual-haptic asynchrony judgments is investigated. It is found that subjects could easily detect the visual-haptic asynchrony when the stimulus onset exceeds 50 ms. Similarly, in [8] it is shown that during a haptic tapping task with delayed visual feedback, the task performance decreases and the subjective task difficulty increases with growing visual delay. This asynchrony disturbs the user perception and thus needs to be compensated for, or at least reduced.

The state-of-the-art to compensate for the video delay in real TPTA systems is to augment the operator with a so-called predictive display. In [9, 10], a virtual model of the remote environment is overlaid on the real video images and the geometric modeling errors are also dealt with using augmented reality concepts. However, when using graphic prediction only, the predictive contact force is lost. The combination of a predictive display and predictive force feedback is successfully addressed in [11], where the predictive haptic and visual signals are synchronized. The predictive display approach, however, asks for a precise geometric model of the remote environment. If the TPTA system works in a complex and visually rich environment (complicated geometric features, textures, dynamic environment), it is difficult to extract such information. In this case, rather than applying the predictive display method, it is preferable to watch the delayed real video directly, with no loss of precision and detail. Thus, a better method is needed to compensate for the asynchrony between the visual and haptic feedback signals.

In this paper we describe a novel approach that compensates for the asynchrony between the haptic and visual feedback and reduces the model-jump effect for MMT. Similar to [3, 4], simple surface models of the remote environment are built using distance sensors to generate haptic signals locally on the OP side. These surface models are invisible to the user. To compensate for the visual-haptic asynchrony and reduce the model-jump effect, we change the position of the virtual surface model on the OP side by shifting it along the motion direction of the OP. Thus, the model rendering is locally delayed and the visual-haptic asynchrony as well as the model-jump effect are compensated for (or at least reduced). As

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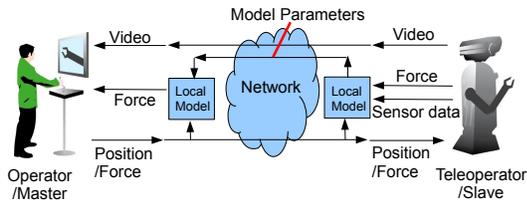


Figure 1: Overview of a MMT system (adopted from [3]).

the haptic signals are still rendered locally without delay, the system remains stable. We refer to the proposed extension of MMT as model-displaced teleoperation (MDT). Two experiments in this paper are conducted to find out the optimal displacement compromise and show the improvement both in subjective quality and task performance for MDT.

The remainder of this paper is organized as follows. Sec. 2 briefly reviews the concept of MMT. Sec. 3 explains the proposed approach. Sec. 4 describes the design of the experimental evaluation and summarizes the results. We conclude this paper in Sec. 5.

2 MODEL-MEDIATED TELEOPERATION

MMT [3] uses the position of the slave robot and the force/torque feedback signals to build a virtual model of the remote environment. The model parameters are transmitted to the OP side where a local virtual model is constructed accordingly. While the user interacts with the remote environment, the haptic feedback is generated locally without any delay based on this virtual model. On the TOP side, the slave is position-force controlled [3, 4] (Fig. 1).

The control schemes for the slave and master side in [3] and [4] are as follows. The force to be displayed by the master is:

$$F_m = k_p^m (x_{proxy} - x_m) \quad (1)$$

where k_p^m , x_{proxy} and x_m are the environment stiffness (received from the TOP), the proxy (for haptic rendering) and master positions, respectively. The slave is position controlled in the direction tangent to the planar surface and force controlled in the direction perpendicular to the planar surface:

$$F_s = F_{pd}^* - F_m \quad \text{with} \quad F_{pd}^* = \max(F_{pd}, F_{thresh}). \quad (2)$$

where F_s is the slave force, F_{pd} is the proportional-derivative (PD) control force command on the slave side and F_{thresh} is set as the maximum PD force [3].

In the following, similar to [3, 4], the environment is locally approximated by a frictionless planar surface. Distance sensors on the TOP side are employed to estimate the environment geometry. Different from [4], the object surface in the remote environment is considered to be non-rigid and its stiffness varies spatially. As stated in Sec.1, the visual-haptic asynchrony grows with increasing communication delay. Additionally, model updates lead to the model-jump effect which jeopardizes the system performance [5]. In the following subsections we discuss the visual-haptic asynchrony and model-jump issues of the original MMT in detail.

2.1 Asynchrony in Visual-haptic Feedback

The left-hand side of Fig. 2 illustrates the delayed video feedback of the slave position on the TOP side as it is displayed to the operator. The right-hand side shows for the same time instant the estimated local virtual model and the current position of the master on the OP side. The haptic feedback is rendered locally without delay which results in a visual-haptic asynchrony. The master gets in contact with the local virtual model and generates a haptic

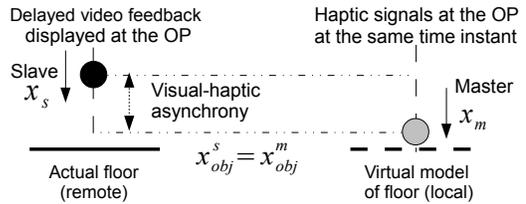


Figure 2: Visual-haptic asynchrony for 1-DoF MMT with communication delay. The user experiences the collision haptically T_d (round-trip delay) before seeing it visually. x_{obj}^s and x_{obj}^m are the real floor position on the TOP side and the virtual floor position on the OP side, respectively.

contact signal before the contact actually occurs in the remote environment. This implies that the displayed haptic signal is always ahead of the displayed visual feedback signal in a TPTA system with communication delay. This can also lead to a haptically unexpected collision, which refers to the situation where the users watch the feedback video and see there is still a distance between the slave and environment, while the haptic contact signal is already locally generated and displayed through the haptic interface to the users. Therefore, our hypothesis is that, due to the unexpected collision, the contact force at the collision time instant is beyond the control of the user and the slave as well as the environment may experience undesired collision forces.

2.2 Model Jump Effect

For remote object surfaces with spatially varying stiffness, the virtual plane position and orientation can be estimated on the TOP side before the slave gets in contact with the environment, while the plane stiffness can be only estimated after that [4]. As the haptic force is rendered locally without delay based on the virtual model and the master position, an initial estimation of the plane stiffness on the OP side is necessary. After the actual stiffness value from the TOP side arrives at the OP side, the stiffness of the local virtual plane is updated. If the initially estimated stiffness $k_p^{m(init)}$ is softer (under estimation) or harder (over estimation) than the measured stiffness k_p^s , the user experiences the so-called model-jump effect [5]. Fig. 3 illustrates the model-jump effect for an under estimated object stiffness. After the OP receives the measured environment stiffness k_p^m from the TOP side, the stiffness of the local virtual plane on the OP side is updated from $k_p^{m(init)}$ to k_p^m . As a result, the corresponding master force from Eq. (1) increases during a short time. For both under and over estimation, the fast and unexpected force change on the OP side degrades the user experience [5]. In addition, on the TOP side the behavior of the slave may become uncontrollable and dangerous if it receives and applies the changed force from the OP side (slave in force controlled mode, Eq. (2)).

In general, with the described issues of the MMT method the users experience difficulties in controlling the applied force and estimating the environment properties. Therefore, the degradation of the system performance caused by the visual-haptic asynchrony ([6] and Sec. 2.1) and the model-jump effect needs to be compensated for.

3 MODEL-DISPLACED TELEOPERATION

In this section, we describe the details of our proposed MDT approach for compensating the visual-haptic asynchrony and avoiding the model-jump effect. As discussed in Sec. 2, the remote environment is locally approximated by a frictionless planar surface with spatially varying stiffness located in 3D space. The position and orientation of the plane can be determined using distance sensors

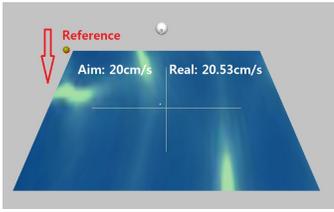


Figure 5: The virtual environment in the first experiment. The orange ball moves vertically with the target velocity as a reference. The big white ball is the HIP of the operator and the white point on the plane is the projection of the HIP.

Task Description and Experimental Procedure Subjects are asked to control a haptic interaction point (HIP) with constant velocity to touch a 3D plane in the virtual environment several times (Fig. 5). As the velocity \dot{x}_m is the key parameter in this experiment, we provide visual and numerical instructions for the subjects as a reference. By following the motion of a reference ball and watching the numerical instructions, the subjects can adjust their movement velocity closely to the target velocity (see Fig. 5).

The starting position of the HIP is about 10cm (non-scaled) above the 3D plane. The visual feedback on the monitor is delayed according to the assumed round-trip delay T_d . The target exploration velocities are 5cm/s, 10cm/s, 20cm/s and 35cm/s and the delays are 50ms (small), 200ms (medium) and 400ms (large). The tested displacement limits are $x_{limit} = \{0\text{cm}, 2\text{cm}, 3\text{cm}, 5\text{cm}, 8\text{cm}, 12\text{cm}\}$ (0cm-shifting corresponds to the original MMT approach).

The experiment has 3 sessions. Each session has a fixed round-trip delay (50ms, 200ms and 400ms) and 24 rounds (4 target velocities \times 6 plane displacement limits). For each round the target velocity and displacement limits are chosen randomly. Before the experiment, a zero-delay case is shown as a reference to the subjects. After each round the user is asked to give a subjective rating for the naturalness of the visual-haptic experience compared to the reference based on a rating scale (1 - completely distorted (unnatural), 2 - disturbing, 3 - slightly disturbing, 4 - perceptible degradation, 5 - no difference with the reference case (natural)).

Then, according to the result of the subjective rating vs. the limits of plane displacement we can find out the perceptually optimal compromise (limit) of the plane displacement value for different exploration velocities and round-trip delays.

4.1.2 Results and Discussion

As shown in Tab. 1 at a velocity of less than 35cm/s all subjects are able to adjust their exploration velocity closely to the target. This result suggests that the user's ability to adapt the velocity to the target is sufficient for target velocities below 35cm/s.

As shown in Fig. 6(a) for 50ms round-trip delay the subjective rating is between 4 (perceptible degradation) and 5 (no difference with the reference case). This result suggests that the subjects are hardly able to perceive a visual-haptic asynchrony of 50ms. This result is not surprising if we consider that previous studies have shown that humans are able to perceive visual-haptic asynchrony only if it is larger than 50ms (e.g. [7]). Considering the nearly flat subjective rating in Fig. 6(a), it is hard to find the optimal displacement compromise. Therefore, we choose the plane shift of 2cm as the optimal compromise, which is enough to fully compensate for the asynchrony for all the investigated velocities for the delay of 50ms ($x_{shift} = 35\text{cm/s} \cdot 50\text{ms} = 1.75\text{cm} < 2\text{cm}$).

For a round-trip delay of 200ms and 400ms the improvement shown by using our MDT method becomes clear. As shown in Fig. 6(b), for an asynchrony of 200ms a higher subjective rating is found for MDT. The perceptually optimal compromise is found, for each velocity except for 5cm/s, at a plane shift limit of 3cm. At a

Table 1: Mean and standard deviation of the measured velocities as a function of the round-trip time

target velocity	Delay 50ms	Delay 200ms	Delay 400ms
5cm/s	5.2±1.2cm/s	5.4±1.6 cm/s	5.2±2.1 cm/s
10cm/s	10.2±2.3cm/s	10.4±2.8cm/s	11.0±2.4cm/s
20cm/s	21.8±2.7cm/s	22.2±3.2cm/s	22.1±4.3cm/s
35cm/s	33.8±5.6cm/s	32.4±7.1cm/s	30.9±9.3cm/s

velocity of 5cm/s, the subjective rating is almost flat (around 4) for a plane shift limit of 0cm to 12cm.

The same tendency can be observed for a delay of 400ms as shown in Fig. 6(c). At a velocity of 5cm/s, except for 0cm-plane shift, the subjective rating is always around 3.5. For higher velocities (≥ 10 cm/s) the turning point is at a plane shift limit of 5cm.

Note that the actual plane shift $x_{shift}^{actual} = \min(x_{shift}, x_{limit})$ is not always identical to the x_{limit} . For example, for the target velocity of 20cm/s with a delay of 200ms in Fig. 6(b), a maximum plane shift $x_{shift} = 20\text{cm/s} \cdot 200\text{ms} = 4\text{cm}$ is enough to fully compensate for the asynchrony. Thus, for the tested shift limits 5cm, 8cm and 12cm, the actual plane shift x_{shift}^{actual} is always 4cm, which leads to a nearly flat subjective rating curve for the range of shift limits from 5cm to 12cm. The same trend can be also observed for other target velocities in Fig. 6(b) and 6(c).

In summary, the experiment shows that for a delay of 200ms and 400ms our MDT approach is able to improve the subjective experience for all the velocities considered. Moreover, for a delay of 50ms, 200ms and 400ms, the optimal compromise of the plane displacement limits is 2cm, 3cm and 5cm, respectively. These values are adopted in our second experiment.

4.2 Experiment B

As discussed in Sec. 2.1 and 2.2, unexpected collisions caused by visual-haptic asynchrony as well as the model-jump effect lead to unstable master force at the instant of collision. In addition, a growing visual-haptic asynchrony increases the task completion time [6]. Moreover, sudden stiffness updates (model jumps) give the user time-variant stiffness information and may lead to wrong decisions when the users are estimating the environment stiffness. Therefore, in the second experiment we consider the error of the applied force, the error of the stiffness estimation and the completion time as the three main factors to evaluate the task performance. Meanwhile, the maximum contact force is also investigated.

In this experiment we apply the previously found optimal displacement compromise on the designed task experiment. The measurement time of object stiffness Δt (see Sec. 3) is neglected.

4.2.1 Experimental Set-up

Participants 17 subjects, new to the study, are selected following the same criteria as in the first experiment.

Materials and Design A Force Dimension Sigma.7 device (master) is operated by the users on the OP side. The TOP consists of a KUKA LWR arm (slave), a JR3 force sensor and a Phidgets distance sensor (range 4-30cm) (Fig. 7). The software environment is based on ROS (www.ros.org) and the H3D library (www.h3d.org). The round-trip delays T_d in this experiment are set to be 50ms, 200ms, 400ms and 1000ms (included to investigate larger delay). The previously determined displacement limits 2cm, 3cm and 5cm are adopted for the delay of 50ms, 200ms and 400/1000ms, respectively.

Task Description and Experimental Procedure The experimental task consists of moving a robotic arm to explore an artificial

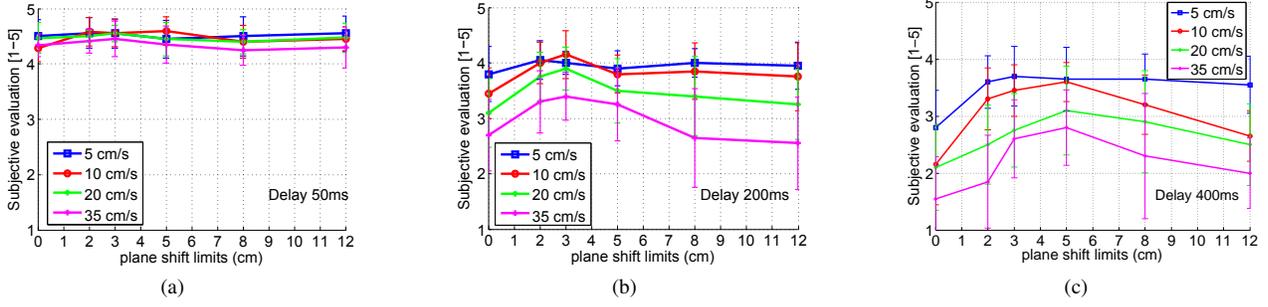


Figure 6: Results of Experiment A. Mean and standard deviation of the subjective ratings vs. the tested plane shift limits for delays of 50ms, 200ms and 400ms and different exploration velocities. A plane shift limit of 0cm corresponds to the original MMT approach in [3]

Table 2: Preference between the MMT and MDT methods.

System Delay	50ms	200ms	400ms	1000ms
MMT	41%	29%	3%	9%
MDT	59%	71%	97%	91%

human liver and to identify the perceived stiffness (Fig. 7). Both subjective evaluation and task performance are investigated.

The artificial liver is divided into three areas of the same dimension. A total of three different stiffnesses are simulated, soft (1N/cm), medium (5N/cm) and hard (25N/cm), and randomly presented during the experiment. In each area, the initial stiffness k_p^m is randomly generated from the three stiffness values at the beginning of each round. The k_p^m is necessary for the original MMT and our MDT with displacement compromise.

Subjects are instructed to move the robotic arm to touch, one at a time, all the three areas and to identify the corresponding stiffness. Subjects are also instructed to control the applied force to the master (less than 4N) and the time used to complete the task (less than 15s). The application of a force bigger than 4N, a task-time longer than 15s and erroneous stiffness identification of the touched area are error conditions of which the subjects are informed in the training session.

Before the start of the experiment, subjects are trained for both force and time control and stiffness detection, ensuring that all participants are approximatively at the same level. Four sessions of two rounds each are performed twice. During each session a specific time delay (50ms, 200ms, 400ms, 1000ms) and two different approaches, one for each round (MDT and original MMT), are applied and randomly presented ((4 sessions \times 2 rounds) \times 2 = 16 rounds).

After each round, the subjective evaluation is collected by a questionnaire with 5-point Likert-scales in it. The questionnaire consists of the following statements: S1 “I completed the task required without any error” and S2 “I had the feeling/sensation that the temporal synchrony between haptic and visual rendering was unnatural”. Point 1 on the scale corresponds to “strongly disagree” and point 5 to “strongly agree”. After each session the subjects are asked to pick-out which round of the corresponding session they prefer (considering naturalness and comfort).

Statistical analysis is applied for the performance data. Two sample T-test and Wilcoxon rank sum test are employed for the parametric and nonparametric data, respectively.

4.2.2 Results and Discussion

As reported in Table 2, a rate of preference (preferred round) bigger than 59% is obtained for our MDT method for all delay values. With a growing round-trip delay, a stronger user preference can be

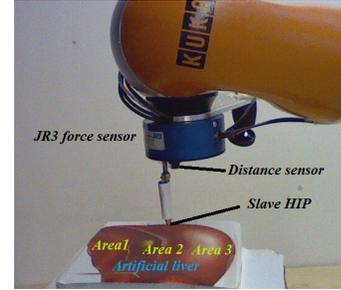


Figure 7: The setup of the second experiment.

observed. For example, for the delay of 400ms, the preference is as high as 97%, which shows a great improvement of user experience for our MDT method. Considering the results of the questionnaire about S2, for all the four delays considered, subjects report a bigger sense of unnaturalness for MMT compared to our MDT method (Fig. 8). Both these results suggest that, compared to the original MMT method, our MDT approach is able to improve the sense of naturalness and comfort due to the reduced sensation of asynchrony and model-jump effect during the collision time.

A different consideration is needed for the results of the questionnaire about S1. For delays of 50ms and 200ms a very close subjective evaluation rating is found, but with a different number of errors (7% and 15% for the MMT and 5% and 8% for our MDT method). These results suggest that when our MDT method is applied subjects are better able to realize if errors are made. Further studies are required to clarify this hypothesis.

As shown in Table 3, more stiffness identification errors are made for the MMT method than for the MDT method and about twice the error rate can be observed when the delay is larger than 50ms. Indeed, with a delay of 200ms, 15% errors are made for MMT, compared to 8% errors for the MDT method. The same trend is also found for a delay of 400 ms (30% compared to 11% errors) and 1000 ms (38% compared to 18% errors). This result gives a clear hint of the task performance improvement obtained, already for delays of 50ms, by using the MDT compared to the MMT method.

The model-jump effect could be the reason for the higher error rate for the original MMT as discussed in Sec 2.2. The suddenly updated environment stiffness disturbs the users’ perception. The users perceive two stiffness values, k_p^m and k_p^m , which could cause an estimation error if $k_p^m \neq k_p^m$.

Similar to the stiffness errors, a smaller error rate of force control is found for the MDT method compared to MMT (Table 3). For the MMT method, for delays of 200ms, 400ms and 1000ms, an

Table 3: Comparison of the task performance between MMT and MDT (total rate, mean value and standard deviation).

Investigated Factors	Delay 50ms		Delay 200ms		Delay 400ms		Delay 1000ms	
	MMT	MDT	MMT	MDT	MMT	MDT	MMT	MDT
total error rate (stiffness)	7%	5%	15%	8%	30%	11%	38%	18%
total error rate (applied force)	5%	3%	16%	7%	29%	14%	45%	21%
mean max. contact force (N)	3.2±1.0	3.0±1.1	3.8±1.1	3.2±1.2	4.2±0.9	3.3±0.9	4.8±1.4	3.7±1.3
mean time consumption (s)	9.8±1.3	9.9±0.9	11.4±1.4	11.1±1.2	13.4±1.6	12.2±1.3	15.6±1.0	14.3±1.3

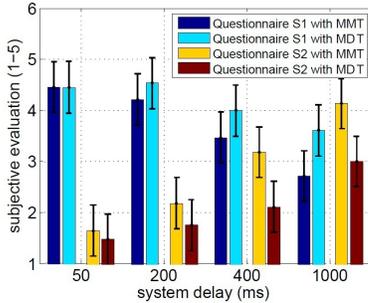


Figure 8: Results of system delay vs. mean and standard deviation of the subjective rating.

error rate about twice the error rate for the MDT method is found. Meanwhile, the mean maximum contact force is more than 0.6N lower if the delay is more than 200ms and the MDT method is employed, which verifies our hypothesis in Sec. 2.1. This result suggests that when the delay is bigger than 50 ms, if our MDT method is employed, the subjects are better able to control the applied force, which is mandatory in several contexts like surgical environments.

In Tab. 3, the task completion time is reported. The results suggest that, apart from 1000ms delay, subjects are able to complete the task in time (less than 15ms) for both approaches. A shorter mean completion time is found for the MDT method. As suggested by previous studies [6]-[8], visual-haptic asynchrony increases the time needed to complete the task. In addition, after perceiving the model-jump effect, the users need extra time to re-estimate the environment stiffness. Thus, the results found by our experiment suggest that the MDT method is able to reduce the completion time due to a reduced visual-haptic asynchrony and model-jump effect.

Moreover, according to the statistical analysis, a significant difference between the two approaches for all three factors (stiffness errors, force errors and completion time) is found for the round-trip delay of 400ms and 1000ms ($p < 0.05$), which confirms that our MDT method improves the task performance significantly for large delays.

In summary, these results show that an improved sense of comfort and naturalness is found for the model displacement method. In addition, a higher level of task performance is reached.

5 CONCLUSION AND FUTURE WORK

In this paper, we present a novel approach to compensate for the asynchrony between the haptic and visual feedback signals and reduce the model-jump effect for model-mediated teleoperation with real video feedback. For a complex dynamic environment, using a predictive display is not an option. Instead, real video captured on the remote side is displayed on the operator side. However, this leads to a round-trip time dependent asynchrony between haptically and visually displayed events as well as perceivable distortions due to the model-jump effect. A model displacement algorithm is applied to compensate for this asynchrony and to reduce the model-jump effect compared to the original MMT approach. As the haptic signals are still rendered locally, the system remains stable even for

significant communication delays. Compared to the original MMT approach, the subjects report an improved quality of experience for our MDT method. In addition, they are also better able to control their applied force more accurately if our MDT approach is employed. Moreover, our MDT approach shows a reduction of the task error rate by more than 50% and the task performance is significantly improved for large communication delays.

In future work, we plan to evaluate our MDT approach for more complex environments, including dynamic, deformable objects. In addition, the jitter of the communication delay will be also considered. Moreover, a depth camera will be used to build more precise virtual models of the object surfaces in a real remote environment.

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