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Quality-of-Task Perception-based Optimization of Time-Delayed Teleoperation Using a Hybrid Passivity-Digital Twin Control Strategy

Siwen Liu
Chair of Media Technology
School of CIT
MIRMI
TU Munich
Munich, Germany
siwen.liu@tum.de

Mads Antonsen
DIGIT group
Dept. of ECE
Aarhus University
Aarhus, Denmark
m.m.a@ece.au.dk

Xiao Xu
Chair of Media Technology
School of CIT
MIRMI
TU Munich
Munich, Germany
xiao.xu@tum.de

Zhi Jin*†
*School of Intelligent Systems Engineering
Shenzhen Campus of Sun Yat-sen University
Shenzhen, China
jinzh26@mail.sysu.edu.cn
†Guangdong Provincial Key Laboratory of
Fire Science and Technology
Guangzhou, China
jinzh26@mail.sysu.edu.cn

Eckehard Steinbach
Chair of Media Technology, School of CIT, MIRMI, TU Munich
Munich, Germany
eckehard.steinbach@tum.de

***Abstract*—This paper introduces a hybrid passivity-digital twin (P-DT) control strategy for teleoperation to enhance haptic feedback in partially unknown remote environments. While Digital Twin-based teleoperation mitigates communication delays through model-based interaction, it may provide less accurate force feedback when the model is insufficiently developed. To address this, the proposed hybrid P-DT strategy dynamically switches between passivity-based and Digital Twin-based control modes, depending on the quality of task perception (QoTP), which reflects the quality of the Digital Twin model. Passivity-based control is used to ensure stable but distorted feedback during the modeling phase. DT-based control provides accurate and responsive feedback once the QoTP metric indicates sufficient model quality. Experimental results under various delays and model update conditions show that the hybrid P-DT strategy outperforms standalone passivity-based and DT-based methods, with subjective quality ratings improving by up to 80% under a 150 ms delay.**

***Index Terms*—Hybrid P-DT control strategy, QoTP, Haptic Teleoperation.**

I. Introduction

Human-in-the-loop teleoperation with haptic feedback represents a key application scenario of the Tactile Internet (TI) [1]. A basic haptic teleoperation system structure is shown in Fig. 1. The leader device (namely the haptic interface), manipulated by the operator, transmits the position/velocity signals via a communication network. The follower device (namely the remote robot), interacting with the real/virtual environment, sends the corresponding force feedback (force, torque) with audio/video data streams back to the operator. This bilateral data exchange allows the operator to perceive immersion locally, enabling the adjustment of further movements and facilitating remote tasks such as telesurgery [2], underwater exploration [3], and aerospace applications [4].

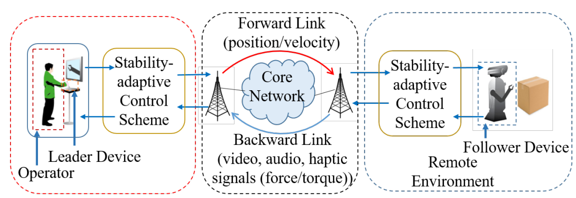

Fig. 1. Overview of a human-in-the-loop haptic teleoperation system (adapted from [5]).

Due to its closed-loop structure, haptic teleoperation is highly susceptible to round-trip communication delay, which can introduce instability [6] and potentially cause physical damage to the system. Several control schemes have been proposed in the control field to mitigate these effects. Passivity-based control schemes such as the time-domain passivity approach (TDPA) [7], [8], ensure stability by dissipating excess system energy. Digital Twin [9]-empowered teleoperation (DTeT) control schemes, also known as model-mediated teleoperation (MMT) [10], use a Digital Twin of the remote environment on the leader side to provide real-time, high-fidelity force feedback without delay.

Passivity-based control ensures stable and reliable force feedback without requiring explicit reconstruction of the remote environment, making it a widely applicable approach for diverse teleoperation scenarios. [11] proposes a hybrid Model Predictive Control (MPC)-based bilateral teleoperation system

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to mitigate abrupt force changes. [12] presents an adaptive energy reference time domain passivity approach to reduce abrupt force variations within the passive control framework. However, the aforementioned systems are conservative, and the impedance error, especially in the force feedback, becomes less realistic as the delay increases.

In contrast, MMT offers a balanced solution, improving system quality, stability, and interaction transparency by delivering high-quality, delay-free feedback locally. Although MMT theoretically provides superior quality compared to passivity-based control methods, mismatches between the digital twin model and the real environment during the modeling phase can result in position-tracking errors and force discontinuities. These will compromise the system's performance and user experience.

To optimize system performance, a combination of passivity-based and DT-based control schemes was proposed to leverage the strengths of both approaches. Xu et al. proposed a delay-driven online control scheme switching strategy to enhance the quality of experience (QoE) [13]. From the perspective of model restoration, the quality of task perception (QoTP) was introduced in [5] to evaluate MMT modeling. It represents the perceptual accuracy of interaction force feedback provided by the DT model. Although simulations in [5] showed that employing QoTP and delay as switching conditions for control schemes can enhance user performance, the environment model is overly simplistic, lacking geometric features. Moreover, a comprehensive switching strategy for the teleoperation system is not addressed.

Therefore, we propose a hybrid P-DT teleoperation system and develop a switching strategy including both physical and geometrical restorations. The geometric modeling approach using Truncated Signed Distance Fields (TSDF) from [14] is extended to generate a Digital Twin restoration that reflects the haptic interaction with the object. The automatic switching strategy considers both the extent of haptic exploration and the authenticity of the force feedback provided by the model.

The rest of the paper is arranged as follows. We introduce the existing relevant system optimizations in Section II. In Section III, the proposed hybrid P-DT approach and the control scheme switching strategy are described. The experiments and results are presented in Section IV. Section V concludes the paper and outlines the direction for future work.

II. Background

In this section, we review existing work on system optimization combining TDPA and MMT.

A. Delay-based Performance Optimization

To reduce the impact of communication delay, a stabilization control enhancement is proposed [15] and improved [16]. A fuzzy-passivity control is introduced for VR interactions [17]. However, the generalization across tasks is limited. The state-of-the-art control method [18] introduces a model-augmentation approach to ensure the safety of autonomous agents, focusing primarily on the network and control quality in terms of energy passivity. Meanwhile, integrating multiple control schemes helps mitigate the limitations of each.

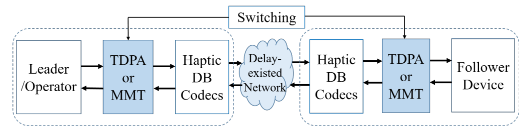


Fig. 2. The human-in-the-loop haptic teleoperation system with switchable control schemes (adapted from [5]).

The P-DT haptic teleoperation system in Fig. 2 includes both TDPA-Energy-Reflection+Deadband (TDPA-ER+DB) [19] and MMT+Deadband (MMT+DB) [20] running in parallel. Research in [21] demonstrates that the switching threshold of delay between TDPA and MMT is around 50 ms: TDPA is more effective below this threshold, whereas MMT outperforms it beyond this point (see Fig. 3(a)). This delay-adaptive switching strategy has been validated through subjective tests in [13]. In these studies, MMT assumes a sufficient understanding of the environment to achieve high-quality modeling. However, in complex scenarios, such as dynamic environments or situations where objects frequently change, the MMT model requires frequent updates to align with the actual conditions, which can compromise modeling accuracy. Under these circumstances, MMT may perform worse than passivity-based methods, even under high-latency.

B. QoTP-based Performance Optimization

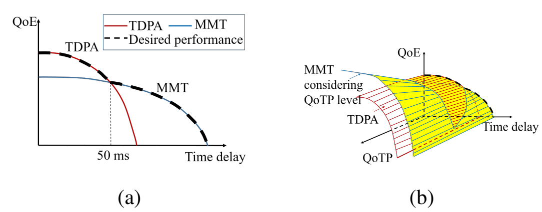


Fig. 3. The control scheme switching point (adapted from [21]) and the switching surface of the hypothetical QoTP-based performance surface (adapted from [5]).

As delay alone is not a sufficient criterion for switching control schemes, it is necessary to consider the quality of modeling as well. To address this, the QoTP metric is introduced, which is incorporated into the control scheme switching strategy outlined in [5]. This allows the switching to not only depend on time delay but also on an understanding of the environment, thereby improving the user experience. According to the illustration in Fig. 3(b), MMT can be selected even with low delay if the QoTP is sufficiently high. Similarly, TDPA can be used in the absence of task pre-knowledge and environmental Digital Twin information, even in the presence of significant round-trip delay.

While theoretical progress has been made by considering QoTP for optimizing user experience, the online automatic control scheme switching strategy remains unimplemented and unverified in [5]. Moreover, the movements and force reflections are limited in a 1-D domain for environmental restoration, and the restoration only emphasizes the physical aspect, ignoring complex geometric conditions.

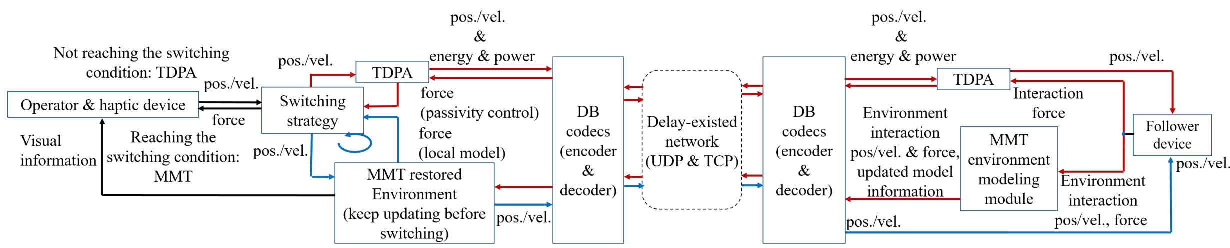


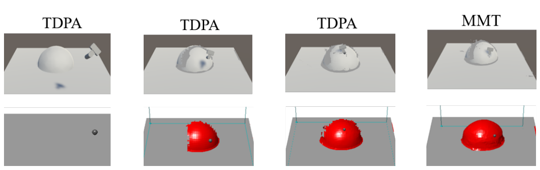
Fig. 4. Detailed structure of the QoTP-based teleoperation system with an auto-switching strategy of control schemes. The position/velocity and force directly captured from the environment is transmitted back for the judgment of the precision of the restored model on the leader side.

III. Method

In this section, we implement the hybrid P-DT teleoperation system, which includes an auto-switching strategy based on QoTP evaluation and an online 3D Digital Twin restoration.

A. System synopsis

In our system detailed in Fig. 4, TDPA and MMT operate in parallel, with only one scheme selected and activated at any given time to control the system. Initially, TDPA is activated to provide stable force feedback but with artifacts, ensuring that teleoperation tasks can still be performed effectively even when the DT model is incomplete. The red and blue lines represent data streams before and after reaching the switching condition. In the communication network, TCP and UDP are used to transmit environment information and haptic signals separately, respectively. DB codecs [22] are coupled in the system to avoid data blocking as well as delayed reception caused by the high transmission rate of haptic data.



(a) (b) (c) (d)

Fig. 5. The process of remote environment exploration in the control-scheme-switchable system in chronological order from left to right. Top four figures: remote environment; bottom four figures: local environment. (a) The system after activation. (b) The visual scanning process. (c) Combining haptic exploration with visual scanning, leading to an increasingly complete model. (d) The auto-switching condition (from TDPA to MMT) triggered by the system's QoTP level.

In the remote environment exploration phase illustrated in Fig. 5, no updated DT model is available at the leader side at the start of the teleoperation, as shown in Fig. 5(a). During the interaction, geometry and kinesthetic information are captured on the follower side according to the visual and haptic signals, indicated in Fig. 5(b) and Fig. 5(c). Mesh models are subsequently generated and iteratively updated using the received environmental data, which progressively refines the model reconstruction on the leader's side. Meanwhile, the system's QoTP improves during the exploration process. Once the QoTP level accurately reflects the situation of the remote environment, the system automatically switches to the MMT control scheme to enhance the force feedback quality, as shown in Fig. 5(d).

B. Model restoration

We introduce the concepts of background and foreground in the context of environmental restoration. Elements that are already known, such as the operating platform in the DT shown in Fig. 5(a), or static features that define interaction boundaries, such as the walls of the environment, are classified as the background. They are displayed to the operator after establishing a connection. The unknown parts and new objects added to the environment belong to the foreground. The foreground requires detailed modeling to estimate both the geometry and impedance, enabling the generation of accurate kinesthetic feedback.

For geometric modeling, we extended the TSDF-based geometric modeling approach [14]. The modeling approach casts truncated rays from the sensor origin to surface points to update the signed distance values of intersected voxels. The marching cubes algorithm on the voxel grid generates a mesh that represents the surface of the remote environment indicated in Fig. 5(b) and Fig. 5(c). The extension allows the system not only to receive the restored model through visual and haptic signals but also to identify whether the mesh model clusters are generated or directly interacted with by the haptic device. Since our research only considers the reconstruction of rigid bodies, we use rigid body impedance parameters to generate mesh model clusters. A mesh model cluster consists of several mesh slices generated in one exploration loop, and the judgment $TM(i)$ of the ith model cluster, supporting the definition of accuracy criteria discussed in the next subsection, is illustrated by:

$$TM(i) = \begin{cases} \text{Haptic-interacted mesh cluster,} \\ \text{if} \quad \text{contact} \;\; \text{and} \;\; Pos_{\text{env}} > Pos_{\text{pf}} \\ \text{Visual-updated mesh cluster,} \;\; \text{else,} \end{cases} \tag{1}$$

where Pos_{env} describes the haptic device vertical position, and Pos_{pf} represents the height of the operating platform surface. This ensures that the interactions focus on the objects rather than the platform. The contact condition becomes true when the interaction force reaches a certain threshold.

Since data collections and the modeling module occupy computing resources on the follower side, we complete the mesh model rendering on the leader side according to the key information updated during the remote modeling shown in Fig. 4. Furthermore, we also design an environment model update method to transfer the restored model from the foreground to the background after the exploration, which enables future update explorations in the remote environment. The details are demonstrated in Algorithm 1.

C. Auto-switching strategy

We establish a restoration precision criterion for environment model reconstruction, serving as a representation of QoTP level to guide the automatic control scheme switching strategy. This criterion includes two factors: the proportion of haptic information coverage P_{h} and the precision of local force feedback S_{h}.

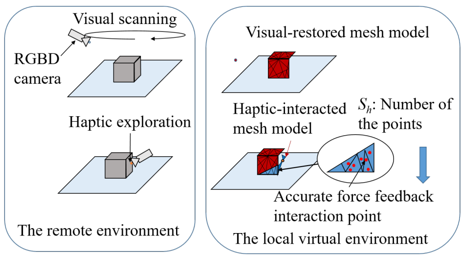


Fig. 6. Model restoration as an illustration for the auto-switching strategy. Blue patches: mesh model clusters updated through haptic signals. Red patches: mesh model clusters generated by the visual information. Light red points: accurate force feedback interaction points.

P_{h} represents the ratio of the mesh model clusters that is updated through haptic signals (shown as the blue patches in Fig. 6) to the mesh model clusters acquired during the exploration (shown as the blue and red patches in Fig. 6). This is defined as follows:

$$P_{\mathrm{h}} = \frac{N_{\mathrm{h}}}{(N_{\mathrm{v}} + N_{\mathrm{h}})}, \quad (2)$$

where N_{h} represents the number of mesh model clusters generated and adjusted by the haptic signals, N_{v} indicates the number of mesh model clusters generated by the visual information. During exploration and reconstruction, visual information facilitates rapid acquisition of object-level details. Haptic signals captured during surface interactions help correct inaccuracies and fill in gaps in areas that are not sufficiently captured by visual data. Therefore, when P_{h} reaches a specific percentage threshold P_{a}, it is considered that sufficient sensor information has been collected for local restoration.

S_{h} represents the number of points (illustrated as the light red points in Fig. 6) that can provide precise force feedback on the restored model during the interaction, defined as:

$$S_{\mathrm{h}} = \begin{cases} S_{\mathrm{h}} + 1 & \text{if } \|F_{\mathrm{env}} - F_{\mathrm{local}}\| \leq AT \\ S_{\mathrm{h}} & \text{if } \|F_{\mathrm{env}} - F_{\mathrm{local}}\| > AT, \end{cases} \quad (3)$$

where F_{env} and F_{local} are the force feedback captured from the remote environment and the local model, respectively, at the corresponding positions. AT represents the threshold for the tolerable force error. If the number of accurate points reaches the threshold S_{a}, we consider that the partially restored model can provide accurate force feedback compared to that from the remote environment.

When S_{h} and P_{h} both reach the thresholds, we believe that the MMT, with a satisfied QoTP level, can outperform the TDPA. The local model restoration is completed and the switching is then triggered, described as TR :

$$TR = \begin{cases} \text{Switch from TDPA to MMT,} \\ \text{if } \ P_{\mathrm{h}} \geq P_{\mathrm{a}} \ \text{ and } \ S_{\mathrm{h}} \geq S_{\mathrm{a}} \\ \text{Keep explorations using TDPA, else.} \end{cases} \quad (4)$$

Since exploration movements vary between operators, there are two possible orders for reaching P_{a} and S_{a}. However, reaching S_{a} first only indicates the quality of the generated local model, not the exploration coverage. On the contrary, if P_{a} is reached first, it indicates that the mesh model's range among the object's surface is sufficient enough, while the accuracy of the force feedback from the local model cannot be guaranteed.

Algorithm 1 Update local model

Input: Q as the queue of restored mesh model clusters.
Output: Q_{u} as updated mesh queue to the background for individual objects, individual object $j \in \{1, 2, ..., N\}$.

while exploring target j **do**
  if IfNewMeshExistedIn($Q_{\mathrm{u}}(1 : j-1)$)==False **then**
    Q=UpdateMesh($Q - Q_{\mathrm{u}}(1 : j-1)$);
  end if
  if Exploration completes **then**
    $Q_{\mathrm{u}}(1 : j)$=InsertMeshFromNewExploration(Q, j);
  end if
end while

IV. Experiments

In this section, we design an object exploration task in a 3D virtual environment to validate the proposed control-scheme-switching strategy. Various conditions of the time delay, control scheme, and QoTP state for environmental restoration based on system computing ability are tested in the experiments. Furthermore, the system's performance is evaluated objectively and subjectively.

A. Experimental settings

The experimental framework is shown in Fig. 7. We use the Geomagic Touch as the leader haptic device. The visual-haptic feedback enables the operator to perceive the rigid-body interaction. A virtual environment (VE) based on Unity is employed to simulate the remote environment. The VE consists of a rigid half-sphere as the foreground with a radius of 0.15 m fixed on a platform as the background. The platform and the leader haptic interaction point are displayed on the leader side when the teleoperation starts. An RGB-D camera with a 360-degree rotation and a resolution of 512×512 pixels is attached to the follower tool point. Since our experiments focus on the combined use of visual and haptic feedback for model restoration, the vision camera is positioned such that it cannot fully capture the back of the half-sphere. The rotation of the touch device pen-tip adjusts the viewing direction of the camera.

B. Operational settings

For objective data collection and subjective tests on user experience, the operational procedure is outlined as follows:

1) In the teleoperation initialization, position control is activated. A cuboid region is selected as the interaction area for both visual and haptic devices.

2) The operator explores this area by scanning and interacting through the haptic point. QoTP of the restored model remains unchanged with repeated contact at the same point.

3) For the subjective tests, taking teleoperation without delay as the reference mode, the operator rates the user experience score according to the haptic information (force feedback) from the local side. The score is set from 1 to 5, representing the worst to the best, and the reference performance is 5.

We set the round-trip delay as 0 ms, 50 ms and 150 ms. DB parameter is fixed at 0.1, which results in approximately a 90% reduction in haptic data during transmission. The switching threshold P_a and S_a representing QoTP level are established as $(50\%, 500)$ and $(75\%, 1500)$, as the usage of different computing resources. The force difference threshold is selected as AT =0.05 N, suitable for the current scenario based on experience. The experiments include three distinct control scheme conditions: TDPA, MMT, and a combination of both integrated with the switching strategy.

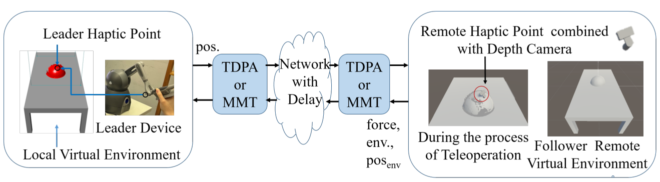
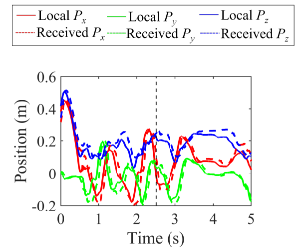


Fig. 7. Experimental setup.

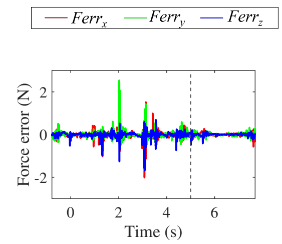
C. Experimental results

For the objective data collection, we record the position and force feedback throughout the interaction with different control schemes. We also invite 11 participants to join the subjective tests. Three of them have experience in haptic teleoperation, while others are new to it or only have a basic comprehension. Our research has been approved by the ethics committee of Technical University of Munich under the number 2023-401-S-NP.

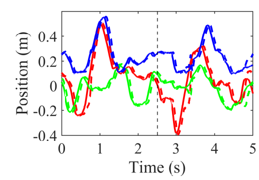
1) Objective results: We record the local and remote position as well as the force feedback on the leader side, selecting the 50 ms-delay condition with a low QoTP level: $(P_\mathrm{a}, S_\mathrm{a}) = (50\%, 500)$. In Fig. 8(a), Fig. 8(c), and Fig. 8(e), solid and dashed lines respectively represent local and remote 3-D positions before and after the QoTP threshold. Fig. 8(b), Fig. 8(d), and Fig. 8(f) demonstrate the errors between local and remote 3-D forces before and after the QoTP threshold. The dotted vertical lines represent the QoTP threshold indicating when the model stops updating.



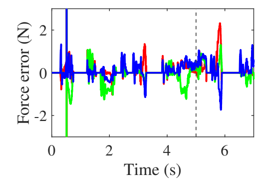
(a) Position performance of TDPA.



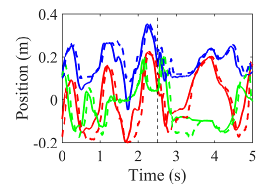
(b) Force performance of TDPA.



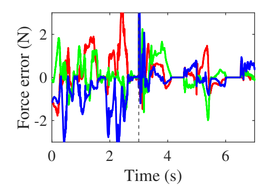
(c) Position performance of MMT.



(d) Force performance of MMT.

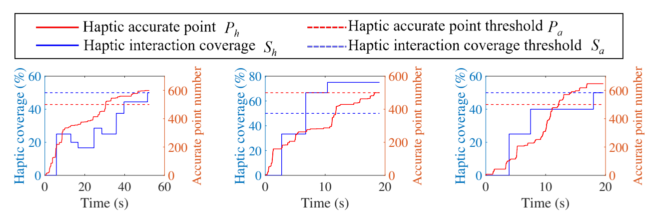


(e) Position performance of combined control scheme.



(f) Force performance of combined control scheme.

Fig. 8. Position and force performance among TDPA, MMT, and the combined control scheme. Delay = 50 ms, QoTP threshold: $(P_\mathrm{a}, S_\mathrm{a}) = (50\%, 500)$. The coordinate system follows Unity's default axis orientation.



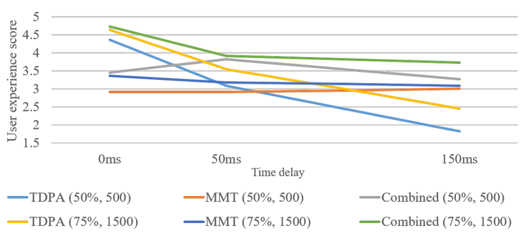
(a) P_h and S_h with TDPA. (b) P_h and S_h with MMT. (c) P_h and S_h with combined control scheme.

Fig. 9. Threshold reaching comparison among TDPA, MMT, and the combined control scheme (single trial per scheme). Delay = 50 ms, QoTP level: $(P_\mathrm{a}, S_\mathrm{a}) = (50\%, 500)$.

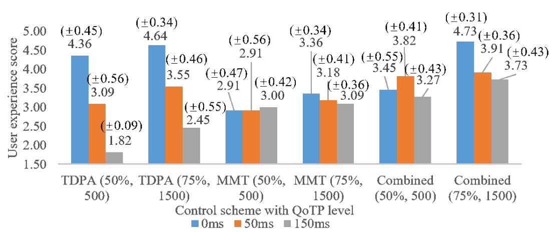
Position performance: According to the results in Fig. 8(a) and Fig. 8(c), MMT achieves better position synchronization, whereas TDPA exhibits additional fluctuations. Our combined scheme aligns with TDPA before the threshold and with MMT after it according to Fig. 8(e). The remaining position errors after switching are from the limitations and imperfections of the restored model.

Force errors: For TDPA, frequent fluctuations in force feedback cause the dense stacking of error bars (e.g., displayed as the blue thicker lines around the x-axis in Fig. 8(b) due to the intensive jitter). In contrast, MMT shows less frequent force errors in general, as these errors are a result of imperfect model restoration. The significant error (partially displayed due to the Y-axis range limit) occurs when a mesh model cluster is generated by haptic signals. Before the mesh model cluster is generated, the haptic point may move into the surface position. Once the mesh model is generated by haptic signals, the point will be pushed back out, reflecting an abnormal force error displayed in Fig. 8(d). Our scheme, as demonstrated in Fig. 8(f), shows force error patterns similar to those observed in the position performance analysis. The abrupt change of the force at the threshold is similar to that in MMT. The difference is that it is caused by the restored local mesh slices rather than by the restoration process itself.

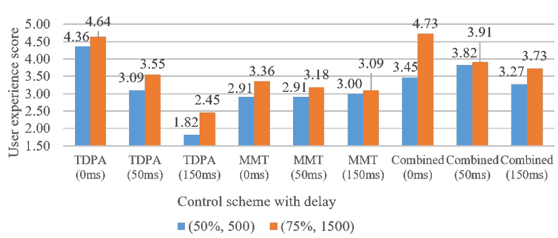
Fig. 9 shows the values of the QoTP parameters among the processes, illustrating the two possible orders for reaching the thresholds discussed in III-B. This decrease of P_{h} is due to an increase in the proportion of visual-generated mesh model clusters during the exploration.



(a) The relationship between user experience and delay.



(b) The relationship between user experience and control scheme with various QoTP levels.



(c) The relationship between user experience and control scheme with various delays.

Fig. 10. The relationship between user experience score and time delay, control scheme with QoTP level and control scheme with delay. Values are rounded for display.

2) Subjective results: The user experience scores under various time delays, control schemes, and QoTP levels are analyzed. The local model updates stop when the QoTP levels are achieved. Interquartile Range (IQR) and Z-score are involved to identify and remove outliers. The average scores of each condition are then calculated. The relationship between user experience and time delay, control scheme with QoTP and control scheme with delay are illustrated in Fig. 10. A three-way repeated measures ANOVA with $p = 1.5 \times 10^{-4}$ indicates significant interaction effects among QoTP, control scheme, and time delay. The 95% confidence intervals are listed above the bars in Fig. 10(b).

According to Fig. 10(a), user experience scores with different control schemes generally decrease as time delay increases. Exceptions to this trend are the combined control scheme with low QoTP level and the MMT scheme. The incomplete model explorations reduce the user experience of MMT and the combined control scheme in the low-QoTP-level scenario. Thus, TDPA providing global force feedback is more effective without delay, also shown in Fig. 10(b).

For MMT under low QoTP, the modeling performance fluctuates, resulting in a better user experience under higher delay. However, the magnitude is minimal and almost negligible. The influence of incomplete model exploration disappears under high QoTP, revealing the impact of delay on MMT's modeling speed. As a result, MMT performance under higher delay reduces, as displayed in Fig. 10(a). Additionally, the modeling performance using MMT is less than that of other schemes, as it lacks the movement restrictions on the leader side.

As illustrated in Fig. 10(c), increasing the QoTP level enhances system performance. In the combined scheme, the restored model with high QoTP level provides more accurate force feedback. However, user experience improvement is less pronounced compared to lower QoTP due to the longer interaction time to meet the switching threshold.

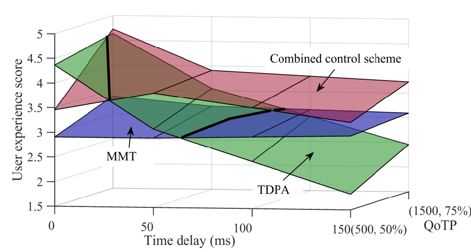


Fig. 11. The human perception score surfaces among TDPA, MMT, and our auto-switching control scheme with various time delays and QoTP levels.

Combining the results in Fig. 10, the final user experience score surfaces are shown in Fig. 11. This proves that the combined scheme with auto-switching strategy is valid in delay-existed real teleoperation systems. The user experience performance is even better than that of using a single control scheme without delay under a high QoTP level.

V. Conclusion

In this paper, we implement a hybrid P-DT teleoperation control strategy to optimize the performance of interacting with partially known environments. The TSDF-based model restoration is extended and we design an auto-switching method to improve the QoTP definition both geometrically and physically. A real-time teleoperation system equipped with the proposed strategy is also developed. In future work, we will focus on flexible objects, where the dynamics should also be considered as an indicator of QoTP.

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