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Trustworthy Delayed Teleoperation via an Imperfect Regolith Model

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***Abstract*— Long-distance teleoperation will enable forthcoming scientific and commercial developments on the lunar surface such as in-situ resource utilisation. However, the large distances involved in these applications introduce multi-second signal delays, which may impair user performance and lead to reduced trust in the system. This work presents a user study of 26 participants exploring the impact of open-loop model-mediated teleoperation (MMT) in providing real-time feedback alongside a delayed video stream of the remote regolith simulant sample collection task. In this system, an imperfect but computationally efficient model was employed to visuo-haptically render the simulant. Three conditions were examined: MMT with visual feedback, MMT with visuo-haptic feedback, and direct teleoperation with delayed visual feedback. Users reported greater trust scores in the visual and visual-haptic MMT conditions (+13%, +12%, respectively) compared with delayed direct teleoperation. In addition, they demonstrated more trusting behaviour in the MMT conditions by reducing the duration of 'wait' periods. Performance metrics were also improved in the MMT conditions (faster completion time), although no significant differences were observed between the two MMT feedback types. These results suggest that, despite using an approximate representation of a complex environment, MMT is a valuable tool for improving performance and developing trust in delayed teleoperation systems.**

***Index Terms*—Telerobotics and Teleoperation, Haptics and Haptic Interfaces, Space Robotics and Automation, Acceptability and Trust.**

I. INTRODUCTION

Robotic teleoperation will enable scientific and commercial activities on the Moon's surface [1] including in-situ resource utilisation of lunar regolith to extract key resources such as oxygen, fuel and construction materials [2]–[6]. Producing these resources in-situ would be a step-change in space sector sustainability, facilitating scientific and commercial exploration activities of the next decade [1].

Teleoperated systems in space must communicate over long distances where physical (speed of light) and practical (transmitting via satellite relays) limits result in disruptive signal delays >2.6s [7], [8]. Not only does this impair operator performance during teleoperation, resulting in slower task completion [9]–[11] and reduced accuracy [12], but also in operators adopting a 'move-and-wait' behaviour [13], during which they spend time supervising the robot's actions [14]. It further damages the human-robot relationship, reducing the operator's trust in the system [14]–[16].

Trust is vital in a human-robot team [17]; even a safe, effective system will only be used if operators trust that it will behave as expected. Yet, few studies have investigated the effects of delay on trust [14]–[16] or methods of addressing this in delayed teleoperation (e.g., haptic feedback [14]). With no delays, haptic feedback improves transparency [18] and situational awareness [19], leading to greater trust [14] as well as improved performance, e.g., reduced contact force and completion times, and increased accuracy and success rates [20]. However, these benefits of haptic feedback do not extend to space applications where multi-second delays occur [14]. One potential method to retain haptic feedback benefits in delayed teleoperation is Model Mediated Teleoperation (MMT), i.e., controlling the delayed remote system via a real-time local simulation that generates sensory feedback [21]. A MMT approach contains the haptic feedback loop within the local subsystem, which is not subject to any delay and therefore ensures stability [21], [22]. While MMT has been proposed to improve trust [23], [24], this remains experimentally untested.

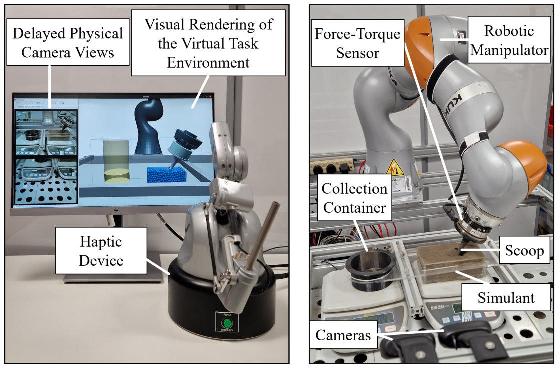

Fig. 1: Local (left) and remote (right) subsystems of the experimental setup.

The effectiveness of MMT relies on having an accurate model of the virtual environment; large virtual-physical mismatches can generate misleading or disruptive feedback [22]. For lunar sample collection, a MMT system requires a virtual model of lunar regolith in a vacuum and under reduced gravity [25]. Highly accurate regolith models exist [26], [27], but are too computationally demanding for real-time sensory feedback. A more lightweight model [25], combining Discrete Element Method with Smoothed-Particle Hydrodynamics approaches, approximates fine-grained regolith as a collection of discrete macroparticles [28], and can be executed at the $\geq$1 kHz rates required for haptic feedback [29], making it a promising MMT option. The accuracy of this model has previously been verified against physical samples of lunar regolith simulant (Exolith LMS-1) [30], and used in an open-loop MMT system for sample collection [24]. Haptic feedback through MMT could assist the user in a regolith collection task via two mechanisms. Firstly, it provides information on whether the end effector is in contact

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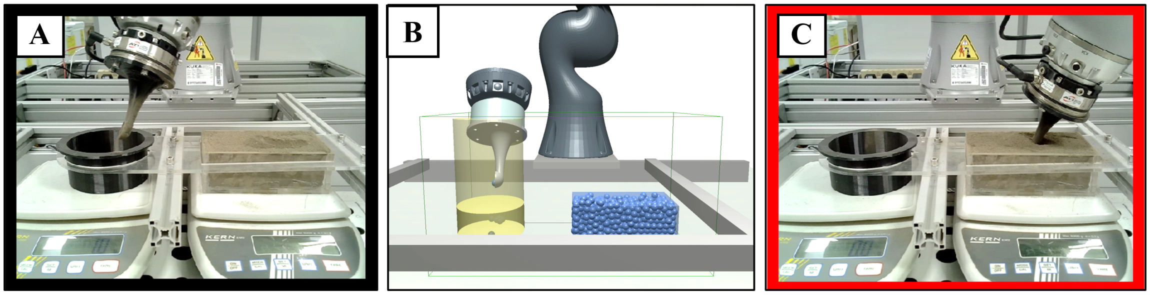

Fig. 2: A: Local monitor display of delayed physical camera view of the task. B: Real-time virtual task environment. C: Visual indication of excessive force displayed as a red border around the camera view of the task.

with the regolith, helping the user to correctly position the tool. Secondly, it provides information on how much regolith is being moved by the end effector, helping the user to reduce excess forces due to 'digging' too deeply and providing real-time confirmation that regolith has successfully been collected or deposited. This additional feedback channel can provide additional information to the operator in situations where vision alone is insufficient for the task. Although it provides an accurate large-scale visual representation of the simulant [30], the haptic feedback is less realistic, due to the discretisation of the granular simulant [24]. However, its impact on operator perception in an unfamiliar environment remains unclear, as it has yet to be evaluated in the context of human-in-the-loop control.

This user study aims to assess this imperfect model as part of an open-loop MMT system during a lunar regolith simulant sample collection task, and to explore the effects of haptic feedback generated in this context to validate whether:

- Open-loop MMT improves trust and/or performance compared with delayed direct teleoperation.
- The haptic feedback generated by the imperfect regolith model improves trust and/or performance.

II. METHODS

A. Sample

The user study was approved by the Research Ethics Committee of the University of Bristol (ID: 2024-17633-19331). All participants enrolled in the study were physically capable of operating the haptic device and reported no known impairments. After receiving an experiment overview, each participant gave informed consent before starting the experiment. The population sample consisted of 26 participants (gender: 2 non-binary, 4 female, 20 male; age: range 23-57, mean 31.6 years; dominant hand: 2 left, 24 right), who were recruited using university mailing lists. The sample encompassed a diverse group, from individuals with extensive experience in robot operation to those with no prior experience. (Daily: 6, Weekly: 4, Monthly: 6, Once or Twice: 7, Never: 3). The sample was skewed towards people who currently play, or have previously played, video games regularly (Daily: 7, Weekly: 4, Monthly: 7, Once or Twice: 3, Used to Play Regularly: 4, Never: 1).

B. Experimental Setup

The experimental setup of the remote subsystem (Fig. 1) comprises a KUKA LBR iiwa14 R820 robot arm with a wrist-mounted force-torque sensor (ATI Axia80-M8) and a 3D-printed scoop (length 7.5cm, internal diameter 2cm, mass 51g, ABS) as the end effector. The arm operated in Cartesian impedance control mode (linear stiffness: 1,000 N m^{-1}, rotational stiffness: 200 Nm rad^{-1} for safe operation during collisions. Two cameras (Logitech C270) captured video streams (640 x 480, 20 fps) from different viewpoints, i.e., one of the task, and one of a set of scales monitoring the amount of collected simulant. 1 kg of lunar regolith simulant (Exolith LMS-1) was placed in a cuboid container (15 x 8 x 5 cm). LMS-1 was selected for its well documented properties, and prior experimentally verification [24], [30]. 7 cm to the left of the simulant, a cylindrical container (10 cm diameter, 5 cm height) served as the target for deposition of the collected sample (Fig. 1). Both containers were within the robot arms's dexterous workspace [31].

The local subsystem (Fig. 1) included a haptic feedback controller (Haption Virtuose Desktop 6D) connected to a laptop (Intel i7-10850H CPU 2.70 GHz, 16GB RAM). ROS-based control software was executed on this machine which also displayed the two camera views – one to monitor the robot's movements (Fig. 2A) and one to monitor the scales to determine whether simulant was successfully collected. A monocular camera view of the task was selected over a stereo view, as the multi-second delays used in this experiment would cause discomfort or motion sickness for the participants if they were to receive the visual feedback via a stereo headset. Cartesian positions were sent from the haptic device to control the remote robot arm with a 1:1 scale mapping. A foot pedal clutch control for the haptic device allowed the user to engage or disengage control of the robot, in order to extend the reachable workspace of the haptic device. A visual indication of excessive physical contact forces measured by the local force-torque sensor was displayed as a red border around the camera streams (Fig. 2C). This threshold was set at 5 N for safety and was determined to be a suitable value for the task during a pilot experiment.

The remote task environment was replicated in a simulation, built using the Chai3D library [32], executed on the local laptop. The simulation (Fig. 2B) included representations of the end-effector, simulant container, and target container. The Pereira & Schmidt regolith model [25] with improved efficiency [30] represented regolith as a collection of viscoelastic macroparticles (radius = 5.5 mm) with the density, cohesion and internal friction parameters equivalent to the specified values for LMS-1 (density: 1,470 kg m^{-3}, cohesion: 0.393 kPa, internal friction coefficient: 0.284). This simulation visually rendered the virtual task environment, from a similar angle to the physical cameras, and haptically rendered the scoop-regolith interactions. A static, monocular view of the simulation was provided to the user, in order to allow for a fair comparison between the test conditions.

C. Experimental Procedure

Similarly to previous evaluations of this regolith model, an example task was selected based on sample curation operations [24]. Participants used the scoop to transfer simulant from the container into the target, minimising applied force. This simulated the demands of lunar teleoperation, where avoiding system damage is vital due to challenges of repair and maintenance. Participants repeated this task three times, under three control mode conditions (Fig. 3), ending in a total of nine recorded tasks per participant.

- **Direct Teleoperation (DT):** A unilateral control structure [22] to command the remote physical robot, with no haptic feedback. Position commands are sent directly from the local haptic device to the remote arm, subject to a 1.5s delay. Video streams from the remote system, including visual warnings for excessive force, are displayed locally after a 1.5s delay.
- **Visual Open-Loop MMT (VM):** A unilateral control structure [22] to command the local virtual robot, with a subsequent unilateral control structure to command the remote physical robot, with no haptic feedback from either robot. Position commands from the local haptic device control a local simulation which displays a visual rendering of the virtual scene. The simulation then sends a position command to the remote arm, subject to a 1.5s delay. Delayed visual feedback from the remote system is displayed locally, alongside the simulation.
- **Visuo-Haptic Open-Loop MMT (HM):** A bilateral control structure [22] to command the local virtual robot and apply haptic feedback from the local simulation, with a subsequent unilateral control structure to command the remote physical robot, with no haptic feedback from the physical robot. Forces were sent to the haptic device with a 1:1 ratio to those generated by the simulation. This ratio was selected as the model provides a realistic subjective feel of interacting with regolith [25]. A pilot study of the experiment supported this decision, with the pilot participants reporting that they could feel the feedback without it being disruptive.

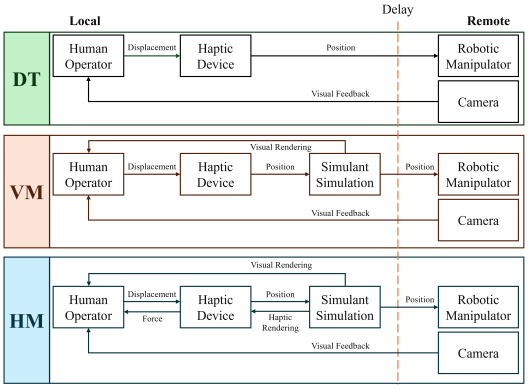

Fig. 3: System diagrams for each of the three control modes: DT, VM, and HM. Information transmitted between the local and remote subsystems, across the red dashed line, is delayed by 1.5s, resulting in a 3.0s total round-trip delay.

The order of these conditions was randomised to reduce training bias [33]. The 1.5s delay each way was selected to represent the Earth-Moon signal propagation times (best-case: 2.6s [7]). It was not deemed necessary to include more delay intervals, as previous work shows trust and performance decline with increasing latency, and, under similar delays, haptic feedback does not improve trust [14].

Participants had 5 minutes of practice before testing, completing the task twice, without communication delays.

D. Metrics

Several metrics were recorded during these trials to determine operator performance and trust over the various conditions, aligned with those used in previous haptic teleoperation user studies [9], [14], [20]. Performance was assessed as:

1) Success Rate: A binary, pass-fail measure. The task was successful if any simulant reached the container. Failures were categorised as missing the simulant during scooping (MS), missing the target during pouring (MP), colliding with excessive force (EF), or reaching joint limits (JL).

2) Mass Collected: The total mass (g) transferred to the target, providing a more granular measure of success than the binary success rate above.

3) Completion Time: The amount of time (s) required to finish each individual task.

4) End-effector Force: The mean and max end-effector force (N) exerted by the remote robot arm's end effector.

Trust was assessed as:

5) Perceived Trust: Schaefer's 14-item trust subscale questionnaire to obtain a self-reported trust score (%) [34]. The shortened version, .was used to reduce fatigue. This questionnaire asked participants to rate on a scale (1-7) whether they felt the robot: functioned successfully, acted consistently, was reliable, was predictable, was dependable, followed directions, met the needs of the task, performed exactly as instructed, had errors, provided appropriate information, was unresponsive, malfunctioned, communicated with people, provided feedback.

6) 'Move-and-Wait' Behaviour: A characteristic of delayed teleoperation , where operators send short movements, pausing to wait for delayed feedback to catch up [13]. This behaviour ('wait' frequency, 'wait' duration and ratio of 'move':'wait') was measured as an indicator of the participants' demonstrated trust in the system, to support the self-reported trust measure obtained from the questionnaire. More frequent or longer 'waits', or a larger proportion of time spent 'waiting' vs 'moving', indicates decreased trust – the rational being that the operator is less confident in sending a long, smooth string of commands, and, therefore, spends more time supervising the physical robot's actions [14].

'Wait' periods were determined by analysing the velocity profile of the commands sent by the operator. Any frame where the velocity was very slow or stopped (linear velocity $<$16 mm s^{-1}) was assigned as a 'wait', with remaining frames assigned as 'move'. This threshold was based on the positional resolution of the haptic device (0.016 mm at 1 kHz). These frames were grouped into 'move' or 'wait' periods based on the assignment of their neighbouring frames. The data were then used to calculate wait frequency (s^{-1}), mean wait duration (s), and move:wait ratio (*Total Move Time / Total Wait Time*). Very short 'move' or 'wait' periods ($<$0.1 s), caused by repeated, rapid switching between assignments, were removed from the analysis, as they were shorter than typical human reaction times to visual or haptic feedback [35] and unlikely due to the operator 'waiting' for feedback. These artefacts were attributed to noise in the velocity data or slow movements close to the velocity threshold.

Alongside these quantitative metrics, participants were observed throughout trials, noting any strategies employed to complete the task.

Differences between samples were analysed for statistical significance using the Statistics and Machine Learning Toolbox of MATLAB. One-way ANOVA (ANalysis of VAriance) was used to compare the results by control mode condition (DT, VM, HM), to identify significant effects on performance and trust. ANOVA was also used to compare results by trial number (first, second, and third, disregarding control mode), to detect any possible practice-related improvements in performance [33]. When ANOVA detected significant differences, post-hoc Tukey's Honestly Significant Difference (HSD) tests were used to identify the specific groups between which there were significant differences.

III. RESULTS

A. *Trust Scores and 'Move-and-Wait' Metrics*

The trust score reported by each individual participant, for each trial, was compared against the corresponding value for each of the three 'move-and-wait' metrics using Pearson's correlation coefficient test. The results of this test detected a moderate negative correlation of wait duration with reported trust score, $r(78)=-0.29$, $p=0.005$. Both, wait frequency and move:wait ratio were moderately positively correlated with reported trust score ($r(78)=0.27$, $p=0.008$; and, $r(78)=0.32$, $p=0.002$). The outputs of these tests reinforce the hypothesis that these metrics are behavioural indicators of trust.

B. *Comparisons by Control Mode*

Fig. 4 and 5 show the mean and standard deviation of each performance and trust metrics, across the three control modes. While success rates were similar across modes, participants completed tasks faster with lower maximum contact forces under MMT conditions (Fig. 4). They also reported greater trust during MMT control modes via their questionnaire responses, and demonstrated this trust through reduced 'move-and-wait' behaviour (Fig. 5). However, there were no distinct differences between VM and HM conditions.

A one-way ANOVA test was performed to compare the effect of control mode on each of the trust and performance metrics from Section II-D. The results of these tests are summarised in Table I. These tests identified statistically significant differences in completion time, wait frequency, wait duration, move:wait ratio, and perceived trust score, between at least two of the control conditions.

Metrics with statistically significant ANOVA test results were interrogated further using Tukey's HSD test, which detected significant improvements in both MMT conditions compared with DT across multiple metrics (Fig. 4 and 5). For the VM condition, mean completion time (92.2s±33.4), wait duration (0.7s±0.2), and perceived trust score (78%±12) were significantly improved (p=0.001, 0.004, 0.002, respectively) compared with DT (145.5s±71.9, 1.3s±0.8 and 65%±15, respectively). Similarly, for the HM condition, mean completion time (98.3s±38.1), wait duration (0.7s±0.2), perceived trust score (77%±11), and move:wait ratio (0.92±0.55) were significantly improved (p=0.004, $<$0.001, 0.002, 0.015, respectively) compared with DT (move:wait ratio was 0.57±0.26). However, the mean wait frequency in the HM condition (0.83s^{-1}±0.18) was significantly greater (p=0.015) than in DT (0.67s^{-1}±0.26).

No statistically significant differences were detected in task success, mass collected, or mean end-effector force, between the three control modes. There was a marginally significant (p=0.06) decrease in maximum end-effector force in the two MMT conditions compared with DT – VM: 11.6 N (10.83), HM: 11.5 N (10.6), DT: 19.2 N (16.0).

C. *Comparisons by Trial Number*

The ANOVA statistical test did not identify any significant differences between groups based on the trial number for any of the metrics recorded.

D. *Failure Modes*

In unsuccessful trials, failures were mainly due to reaching the robot's joint limits (Table II). Out of the ten failures due to missing the target container, eight occurred in DT, with six these during the first condition – five in DT and one in VM. This suggests that MMT conditions improved pouring accuracy, and that practicing in MMT may have helped to avoid this type of failure.

TABLE I: Results of ANOVA test results for significant differences in performance and trust metrics between the three control modes.

Metric	***F(2,75)***	***p***
Success Rate	1.13	0.330
Mass Collected	1.56	0.216
Task Duration	8.24	<0.001
Mean Force	0.95	0.390
Max Force	2.89	0.062
Wait Duration	8.35	<0.001
Wait Frequency	4.12	0.020
Move:Wait Ratio	4.30	0.017
Trust Score	8.26	<0.001

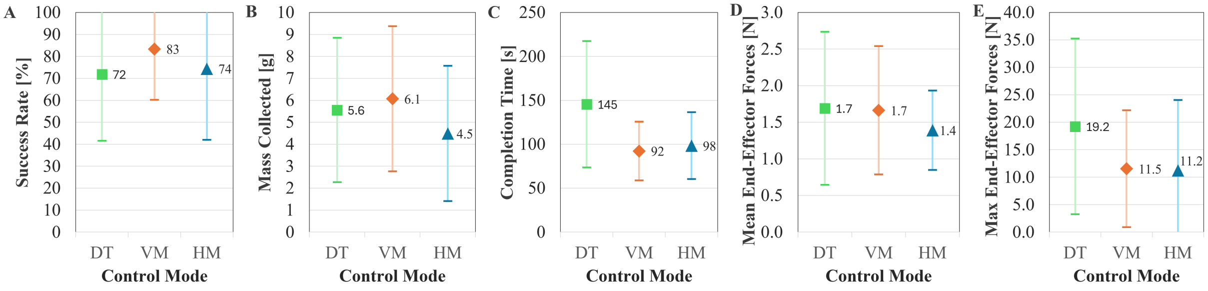

Fig. 4: Performance metrics (Mean +/−SD) for each control mode. A: Success rate, B: Mass collected, C: Completion time, D: Mean end-effector force, E: Max end-effector force.

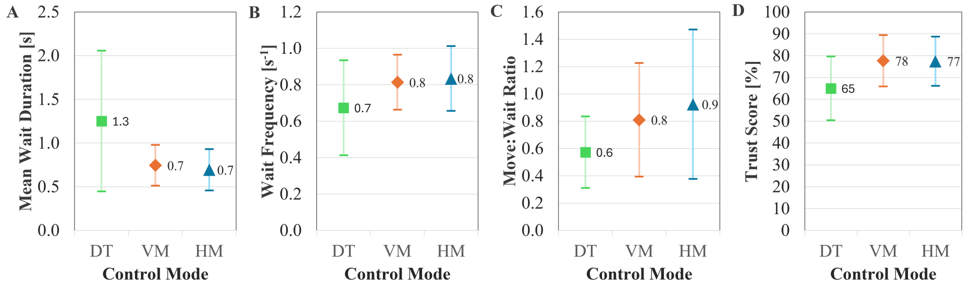

Fig. 5: Trust metrics (Mean +/−SD) for each control mode. A: Wait duration, B: Wait frequency, C: Move:wait ratio, D: Trust score.

TABLE II: Summary of the causes of failed tasks, by trial number and control mode.

	Trial No.			Control Mode		
Failure Mode	**1**	**2**	**3**	**DT**	**VM**	**HM**
Missed Scoop	2	1	1	0	0	4
Missed Pour	6	3	1	8	1	1
Excessive Force	3	1	0	0	1	3
Joint Limits	7	8	7	6	11	5

In VM, the most common failure mode was JL (11 out of 13). In HM, failures varied, including all three incidences of applying excessive forces (all of which occurred during the first trial). Additionally, all failures where participants missed the simulant during scooping were in the HM condition, suggesting that they over-trusted the simulation, and may have been guided by unrealistic haptic feedback.

Figure 4 reports a greater upper limit for max. forces in DT compared with the MMT conditions, whereas Table II reports zero failures due to excessive forces. This inconsistency occurred as a result of the method for triggering the excess force failure threshold. The max. forces reported in Figure 4 were recorded by the 6-axis force-torque sensor at the end effector, whereas the excess force failure was triggered by the internal control software of the robot arm, when a given torque (15 Nm) is exceeded for a single joint. This excess force method is therefore dependent on the specific joint angles at the time of collision.

E. Qualitative Questionnaire Responses

In the comments section of the questionnaire, several participants (identified as **PX**, with X∈[1,26]) reported using the simulation as a guide during the MMT conditions, but making final decisions using the delayed camera feedback. **P6** – “The combination of the simulation to guide [the robot], and the camera to quickly check after the fact how much was picked up.” **P8** – “The simulation really helped at controlling the robot. The visual feedback from the camera is not needed as I did not use it to control the robot. It does help to confirm the position of the robot.” **P21** – “Using simulator to do big moves but using camera to double check on sand pickup (small precise moves)... I trusted the simulation to the point where it touches the sand, then I look at the camera, then I used the simulator to pour.” **P24** – “It’s more useful to look at the simulation [VM].” **P26** – “[VM] was good, especially when I realised that I could concentrate on simulation for the movement and just have to use the real-time to make sure that the contents are transferred fully.” These responses were supported by observations of the participants splitting their focus between virtual and physical visual feedbacks. Questionnaire responses varied regarding haptic feedback. Some participants expressed dislike of the HM condition: **P6** – “Actually a little harder to use with the feedback, sometimes the feedback triggered in midair [due to simulation-reality mismatches] which made me stop. It was only a little useful to tell when I’d hit the top of the dust, which I could gauge from the [VM] simulation easily enough alone.” **P9** – “Haptic feedback would cause me to stutter or flinch causing sharp motions.” **P13** – “The [haptic] feedback felt different to what I expected the dust to feel like. It felt a lot more coarse than I expected” **P21** – “Slight hand cramp on this run. Think I might prefer it without [haptic] feedback”. Others preferred HM: **P7** – “Lack of feedback made it more difficult to tell when the surface was contacted but also made it seem less of an issue to scoop large amounts.” **P8** – “The haptic feedback really does improve the experience.” **P25** – “I think I liked [the haptic feedback] being there but don’t know that it helped with operation. I think the simulation by itself was enough. The vibration from the controller felt like it was trying to warn me about something and made me a bit more hesitant when scooping."

IV. DISCUSSION

A. Impact of MMT vs DT

The results of this study show that participants placed greater trust in MMT conditions, compared with DT, despite any imperfections of the virtual model. This trust was both self-reported (questionnaire) and demonstrated through behaviour such as reduced wait durations (VM, HM), or a greater move:wait ratio (HM). Although 'move-and-wait' is a common coping strategy in delayed teleoperation [13], [14], it results in slower, more disjointed motion profiles which can impair performance. The results demonstrate that MMT can help to alleviate these drawbacks associated, allowing operators to spend more time confidently controlling the robot in a smooth motion profile, rather than supervising the delayed visual feedback from the physical robot. While participants still used 'move-and-wait' in MMT, it was less pronounced than in DT. Instead, a smoother behaviour emerged, where operators relied on immediate (but approximate) virtual feedback from the simulation and only waited briefly to check delayed cameras at key decision points. Participants also completed the task faster using MMT, which would have clear operational benefits in a real lunar system.

B. Impact of Haptic Feedback

Between VM and HM, there were no statistically significant differences in any of the metrics examined. The lack of clear advantages or disadvantages of haptic feedback suggests that it was not a hindrance but largely unused. This may be due to unrealistic haptic feedback generated by the virtual model, as noted by **P14**, or due to individual preferences regarding haptic feedback (Section III-E).

In general, less experienced operators show greater difference between haptic and non-haptic conditions [20]. Expert operators of terrestrial teleoperation systems have expressed mixed views on the inclusion of haptic feedback, influenced by individual experiences or task-specific usage of the feedback [23]. Furthermore, a meta-analysis of real-time surgical robotics studies found that, although haptic feedback improves completion time, contact forces and accuracy, the scale of improvements in some metrics (completion time and contact forces) depends on the type of task [20]. Participants may have obtained little benefit from haptic feedback in this experiment because the task was not well suited to it, or they had not yet learned how to use it effectively.

Unlike previous studies in real-time [20] and delayed teleoperation [9], the haptic feedback provided by this simulation did not significantly reduce the mean end-effector forces. However, mean end-effector forces variance in HM was lower than in both VM and DT, suggesting that the haptic feedback may have resulted in fewer instances of high or low forces. Similar results were reported for a delayed direct teleoperation system [14]. In realistic lunar teleoperation applications, minimising excessive end effector forces is crucial to avoid unnecessary damage to the remote hardware, which is difficult to repair.

Similarly, no clear improvement in path smoothness was gained by adding haptic feedback. Again, this differs from previous studies such as [12], though in that study the largest delay tested was 540 ms.

C. Impact of Trial Number

No significant improvements in performance or trust were exhibited between different trial numbers (regardless of control mode). Considering the randomised trial order, this supports that the significant effects discussed previously are due to the control mode, rather than increasing competency.

Prior work reports that longer training on delayed systems improves performance, with effects lasting up to one week [33]. Trust in a system develops gradually over time [36], [37], and, hence, an increase in perceived and demonstrated trust across subsequent trials would be expected, eventually, if the system was operated without failure over a long period.

The incidence of MP failure modes (Table II) suggests that participants who started with an MMT condition may have learned to avoid this failure mode in the DT condition. Training in simulation has been reported to improve trust [23], i.e., a longer-term study may have elicited a more pronounced change in trust over time.

D. Practical Implications, Limitations and Future Work

This study had mild failure consequences unlike real-world space activities involving severe financial, reputational, and safety risks. The development of the human-robot team in a realistic setting will not be the same as in a brief experiment in a lab environment [38]. Space systems undergo long development times, allowing operators to gradually build trust through early involvement in the design process [23], [39], where human-robot team development would differ significantly.

A limitation of this study is that only one model of lunar regolith was assessed. Other simulations of regolith reported in the literature are currently too computationally demanding to be used in MMT [26], [27], but would warrant further investigation as these are developed further. Alternatively, a simplified model of regolith may be technically feasible which represents the regolith as a 'viscous' block that applies resistive haptic feedback when the end effector is within a defined volume. Similarly, related work identified that the granularity of the virtual regolith will likely impact the 'feel' of the haptic feedback, but this comes as a trade-off against the computational efficiency of the model [24]. Reducing the virtual particle size may offer improvements through providing a 'smoother', more realistic haptic feel; however, the impact of this change on the user's perception is yet to be investigated.

Real-world systems would likely use a more detailed user interface to provide feedback and system information, e.g., by monitoring joint angles, multiple camera views, and supporting task information [40]. Such information may have helped participants to avoid failures such as reaching the robot's joint limits. However, even experienced operators require a support team to monitor these various data streams and provide the most useful information, as needed [23]. To ensure participants focused on the feedback streams (rather than other supporting information) and to determine the impact of the three control modes, this study used a simplified user interface, as none had prior experience with this teleoperation system. Further research is required to optimise integration of MMT with a customisable and informative user interface.

These experiments assumed that the physical robot position tracked accurately with that of the virtual robot, and no synchronisation of the simulation with the real setup or environment reality was required for this short task. During longer use, periodic synchronisation actions may be beneficial as trust in the system would likely degrade as the differences between local and remote increases.

The interaction forces computed by the model were small (<2.2 N), and, therefore, haptic feedback may have been ignored if participants felt it was not aiding them. Although the feedback intensity was set as 100% of the forces generated by the simulation based on the literature [25] and a pilot study, preferences for the ideal strength of haptic feedback vary between operators [41] and this may have differed from the pilot study participants. Operating a larger end-effector to move greater volumes of simulant, or scaling up the intensity of the generated force feedback, could result in more prominent haptic feedback, potentially augmenting differentiation between VM and HM conditions. Alternatively, with more thorough training for participants on how to take advantage of the different feedback streams, a greater difference between VM and HM conditions may have been elicited. In these tests, the highest end-effector forces occurred during contact with the rigid walls of containers (max. 84 N). One explanation of why HM did not significantly reduce end-effector forces compared with VM is that these interactions were not modelled in the simulation. This is comparable to real-world lunar applications, where the robot may make contact with hidden items under the regolith surface that are not modelled in simulation - this challenge could be tested with greater realism in future work by including hidden obstacles buried in the regolith. The visual indicator of excessive force may have also played a role in avoiding these forces during rigid collisions. However, it is unlikely to be the main cause because, as this feedback was subject to a 3 second delay, the collisions would already have occurred before the user could take corrective actions. The visual indicator was present across all three conditions and a marginally significant reduction in max. forces was seen in MMT conditions compared with DT, which may instead be due to fewer overshoots caused by delays, or by the simulation improving participants' spatial awareness to help them avoid collisions with the containers.

There are several dominant state of the art strategies for ensuring stability in delayed teleoperation, such as MMT, TDPA and Wave Variable/Scattering (WV/S) [22]. Most stabilising methods, such as TDPA [42] or WV/S [22], reduce the quality of haptic feedback or position tracking. Therefore, the inclusion of such measures were avoided in this study, which intends to assess the effects of implementing the regolith model in a MMT system. However, the effect of other stabilising methods on trust should be investigated in future work. For example, the improved safety strategies of TDPA [42], [43] allow for faster motions, reducing the need for move-and-wait behaviours unnecessary (although still reducing force feedback quality). This approach may lead to participants adjusting their behaviour, possibly resulting in greater trust in the system. Moreover, TDPA has been extended to use MMT strategies for teleoperation with greater delays [44]. Future work should evaluate the regolith model implemented in this paper, using the updated TDPA-MMT approach [44] to evaluate its impact on trust.

In comparison with DT, the reduced 'move-and-wait' behaviour in both VM and HM conditions suggests that participants may have relied more on the virtual model than physical feedback. Future research could quantify where the participants' attention was placed, e.g., through eye tracking, to optimise MMT implementation and make meaningful design decisions for these systems. The results of this study suggest that MMT without haptic feedback can sufficiently guide the user during some tasks. Operators overlook mismatches between the simulated environment and the real world, providing that any feedback is non-disruptive. Future work should explore a combined approach which capitalises on the benefits of both MMT and other delay-robust haptic controllers such as TDPA [42].

It would likely be advantageous to improve the user's depth perception via a stereo view of task. Observing delayed stereo vision though a virtual reality headset can cause discomfort and motion sickness, therefore, in order to allow a fair comparison between MMT and DT, stereo views were not used in this study. However, the MMT system presented in this study could be adapted to provide operators with a sense of depth, either by providing a real-time stereo view of the simulation or by enabling users to move the virtual camera viewpoint around the scene.

V. CONCLUSION

Open-loop MMT improves trust and performance during teleoperation with multi-second delays. Even with an imperfect model of regolith simulant, operators completed a sample collection task faster and reduced 'move-and-wait' behaviour. These improvements would benefit time-sensitive lunar operations [45]. While sharp feedback changes from simulation updates are often cited as a drawback of MMT in delayed teleoperation, this study demonstrated the effectiveness of an open-loop MMT system which avoids this issue, despite the imperfect real world representation. This approach can support operators in delayed teleoperation, and should be provided alongside other information streams.

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