Evaluation of Performance and Mental Workload during Time Delayed Teleoperation for the Lunar Surface Construction

Miran Seo, Samraat Gupta, and Youngjib Ham, Ph.D.

Abstract— **Teleoperation is critical to accomplish the mission of building planetary habitats and exploring space. However, time delay in long-distance remote-control conditions is inevitable, and it affects operators' performance and mental workload by degrading control accuracy and situational awareness. We developed virtual environments to evaluate the performance and mental workload in three teleoperation scenarios while performing construction tasks from the Moon's surface, on-orbit, and on Earth. The results demonstrate that time delay affects not only degrades the operator's performance and mental workload but also changes control strategies. Future work will explore enhancing the operator's performance and mitigating mental workload by assisting human-robot interactions.**

I. Introduction

Autonomous robots are essential technology to explore extraterrestrial environments. Although the mission of building sustainable habitats on the Moon is challenging, construction in lunar surface terrain has become feasible with novel technologies. However, the Moon's surface remains an unknown and unstructured environment in nature and lies in severe weather conditions for human activities. Teleoperation will play a key role in a human landing on the Moon and building habitats under unpredictable circumstances. Communication time delay in space is a critical hindrance to teleoperation systems that need to interact with humans and robots. Prior studies found that performance degradation and workload generally increase under time-delayed teleoperation conditions such as surgical surgery, on-orbit docking, navigating rovers, etc. There is a dearth of studies on its impact of construction tasks. This paper will contribute to understanding the time delay effects on the construction task performance and operator's mental workload by simulating and evaluating the construction teleoperation tasks.

II. Related Work

A. Time Delay Estimation for Space Teleoperation

Distance and communication networks are major factors in determining the latency between two received signals from human operators and robots in teleoperation systems.

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Distance: The average distance between the Earth and Moon is about 36,000km, and Earth and low Earth orbit (LEO) is about 400km. The round trip time, as the speed of light limit from Earth to the Moon's surface, is a minimum of 2.5 to 3 seconds [1]. The international space station (ISS) or lunar orbit platform-gateway (LOP-G) accessible to the teleoperation system will be orbiting LEO and lunar orbit. The on-orbit serving vehicles enable the signals to reach even the far side and have a wider range of access.

Communication networks: Teleoperation systems consist of complex and multilayered system architectures affecting the latency range. Latency in teleoperation systems occurs from processing, transmission, and propagation delays [2]. Bandwidth types determine an operational time window and transmission quality since bandwidth decides the time to send the layered signal to the channels [3]. Tracking and data relay satellites (TDRS) placed in the Geostationary Orbit (GEO) transmit the signals between receivers for deep space networks.

B. Construction Environments and Challenging Tasks

Construction is activities carried out under unstructured and complex in-situ environments. Tasks are inherently considered "dull, dirty, or dangerous" in extraterrestrial terrain, so there is a need for remote control or fully autonomous robots [4]. Work performance decreases in unpredictable and unstructured environments, including dust, dense regolith, time-varying illumination, and temperature. As the initial phase for the construction site preparation phase, teleoperated robots shall execute clearing rocks, excavating, grading, and compacting the site for the desired terrain. The experimental tasks in this study are attributed to activities of construction site preparation.

C. Situational Awareness in Teleoperation

A visual display is an imperative component for long-distance remote-control teleoperation. Operators obtain situational awareness through visual search, perception, representation processing, and decision-making [5]. However, the extraterrestrial terrain lacks visual information, such as eye-ground elevation for references and size constancy scaling information for operators that indicates depth and distance [6]. The differences in environmental characteristics and difficulties in situational awareness in limited visual information affect task performance and mental workload, including increasing fatigue and cognitive load. The increasing mental workload possibly results in operators' confusion, time pressure, operational efficiency reduction, or operation mistakes [5] [7]. Therefore, there is a need to extend situational awareness while performing teleoperation by enhancing human-robot interaction and assistive interface.

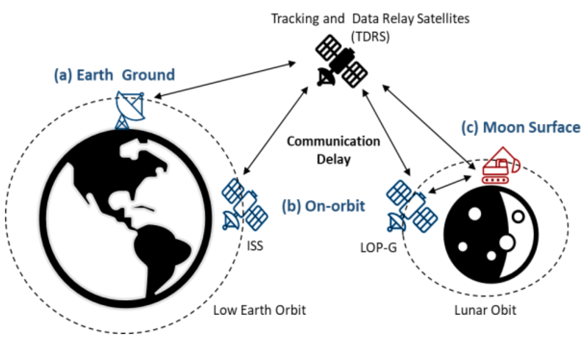
III. Experiments

A. Time Delay and Task Scenarios

Time delay conditions: For this experimental study, the VR simulation was designed with three conditions which are no delay, 1.5s, and 3s delay. The delayed time reflected the distance between robots situated on the lunar surface and the operators' locations which are the Earth's ground (3s), on-orbit vehicle (1.5s), and Moon's surface (no delay). Figure 1 illustrates the conceptual teleoperation communication delays in the deep space network system and human-robot interactions. In this study, time delay refers to the latency between the user's input and its displayed response.

Construction Tasks: A task was to move three rocks to the target area in the VR model simulated for the lunar surface construction context. Clearing the site and removing rocks or obstacles are required activities in the initial site preparation phase. Participants manipulated the teleoperated excavator robot in the VR experimental environment to implement the task.

Figure 1. Conceptual diagram of communication delay and transmission of teleoperation system for space construction.



B. VR Environments and Workstation Set-up

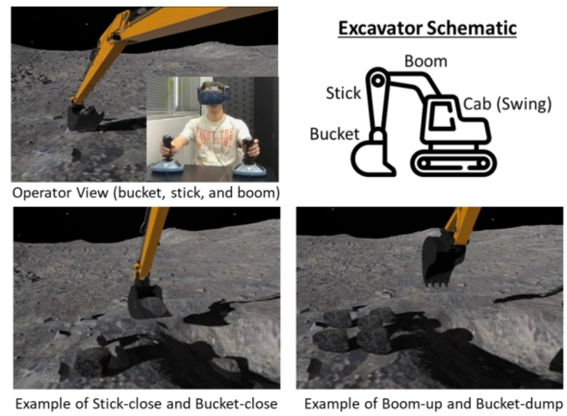
We developed a virtual environment that simulates the lunar surface terrain and surroundings. The simulated view was displayed with a headset, and manipulation input was linked with ambidextrous joysticks (Figure 2). This experimental simulation did not provide sound effects to the task environment by taking account of the Moon's surface nature.

C. Experimental Procedures and Data Collection

The participants (N = 12, 10 male and 2 female) who are Texas A&M University students (M = 23.8, SD = 3.2) conducted construction tasks in three different delay conditions. Their experiences in VR and joystick controllers were varied. Participants completed the tasks under three conditions; 0s, 1.5s, and 3s. After performing each session, they filled in questionnaires set on NASA-TLX (task load index) [8] and VR experience (i.e., immersion and joystick control). NASA-TLX includes six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each session's given tasks were identical except for the time delay condition.

Participants practiced the excavator's manipulation until they were familiar with the control before starting the experiments. To prevent cumulative effects, we limited the maximum performance time to 10 minutes, and the delayed time sessions were given randomly after the no-delay session. We measured the work performance time and collected answers from NASA-TLX, VR experience questionnaires, and eye-tracking data from the VR headset.

Figure 2. VR environment and excavator schematic. The joystick control patterns include cab swing (left and right), boom (up and down), stick (away and close), and bucket (close and dump) motions.



IV. Results and Discussions

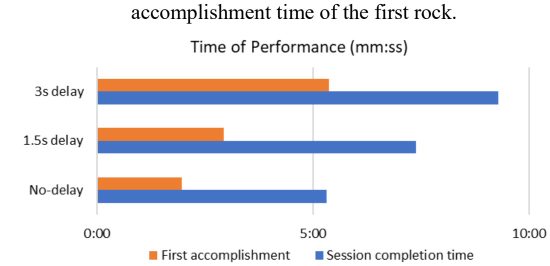
A. Work Performance Evaluation

Participants' completion time was increased in the 1.5s (139%) and 3s (174%) delay sessions compared to the no-delay conditions (Table I). The difference in increased time could be longer at the delayed condition since there had been a limited time (10 min.) in this experiment. One participant's data was excluded from the analysis as the participant failed all sessions and had no data on the first accomplishment.

TABLE I. Work Performance Evaluation

Time delay condition	Performance (N = 11)		
	Completion time (sec)	***Accomplishment of the first rock (sec)***	***Success rate***
No-delay	M = 319, SD = 163	M = 118, SD = 80	91 %
1.5s	M = 443, SD = 131	M = 176, SD = 104	82 %
3s	M = 556, SD = 66	M = 322, SD = 149	45 %

Figure 3. Comparison of completion time of the session and accomplishment time of the first rock.



We evaluated the accomplishment time of moving the first rock to the target area to observe the time of participants' adaptations of control and visual information at each session. As a result, the time was significantly increased in the 1.5s (149%) and 3s (273%) delayed conditions compared to no-delay. The time of the first accomplishment took over 5 minutes in case of the 3s delay (Figure 3). It indicated that the adaptation in delayed conditions took much longer and that the delayed controller action and visual information led to significant work performance degradation.

B. Mental Workload

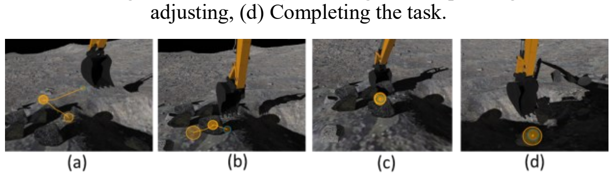
As a result of the assessment of NASA-TLX scores, the mean of total scores that included six dimensions significantly increased as the delay increased. Mental demand and frustration were affected by delayed conditions and showed significant differences in score comparisons (Figure 4). Some participants reported feelings of frustration and difficulties when they made errors and mistakes in joystick manipulation with delay conditions. We confirmed that delayed time caused more mistakes and errors in controlling joysticks, and those led to the operator's frustration, mental demand, fatigue, and discomfort.

Figure 4. NASA-TLX scores. (a) Participants' total scores of the sum of six dimensions, (b) Comparison of mental demand, (c) Comparison of frustration. Note. $^{*}p < .05$.

C. Human Interactions in Time-delayed Teleoperation

Eye-tracking: To investigate the effect of the operator's interaction with eye movement in time-delayed conditions, we observed eye-tracking data and found that participants' rapid movement between eye fixations (i.e., saccade) tended to slow when adapting to the delayed situation compared to no-delay. We found the potential that eye-tracking data allow to estimate the operator's situational awareness, mental workload, and visual demand in time-delayed teleoperation (Figure 5). For further study, we can analyze operators' performance processes by assessing eye movement data such as fixation, saccade, blink rate, etc.

Figure 5. Eye-tracking and situational awareness while performing a task. (a) Finding a target rock, (b) Assessing the distance for controlling the excavator, (c) Focusing on manipulating and adjusting, (d) Completing the task.



Operation strategy changes: Prior studies revealed that an operator tended to "*move and wait*" to adapt to delayed conditions [1]. In this study, we observed participants changed their strategies to avoid errors by waiting and predicting the moment to act between the immediate controller action and delayed visual response. Participants demonstrated that their strategy changes can help to mitigate the difficulties of joystick control and to adapt to delayed visual display during experimental studies.

V. Conclusion

This study explored the effects of time-delayed teleoperation on extraterrestrial construction and evaluated human performance degradation and mental workload increase by experimental study in the construction context. In addition, we observed and discussed the effect of time delay teleoperation on human operators' situational awareness and behavior changes. Further study will investigate and validate the impact of human-robot interactions in teleoperated space construction with multiple evaluation metrics including human mental workload, situational awareness, and behavior changes in time delayed conditions.

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