# Evaluation of Work Performance, Task Load, and Behavior Changes on Time-Delayed Teleoperation Tasks in Space Construction

Miran Seo[1]; Samraat Gupta[2]; and Youngjib Ham, Ph.D., A.M.ASCE[3]

[1]Ph.D. Student, Dept. of Construction Science, Texas A&M Univ., College Station, TX. Email: miran@tamu.edu
[2]M.S. Student, Dept. of Computer Science and Engineering, Texas A&M Univ., College Station, TX. Email: samraatg@tamu.edu
[3]History Maker Homes Endowed Associate Professor, Dept. of Construction Science, Texas A&M Univ., College Station, TX. Email: yham@tamu.edu

## ABSTRACT

A robust teleoperation system has the potential to play a key role in mission tasks relevant to construction in a physically challenging environment. Here, the communication delay generated by long-distance and data transmission in teleoperation systems impacts human–robot interactions and work performances during the teleoperation. There is a need for more understanding of how time delay affects performance in construction activities and human operators' abilities, such as situational awareness and mental workload. This exploratory study aims to provide knowledge on the latency impacts on work performance and task load by measuring and evaluating the relevant human factors. Participants conduct construction tasks under time-delayed conditions in virtual reality environments. We assess the performance (i.e., completion time, success rate) and task load (i.e., mental demand, frustration) and observe manipulation behavior changes to evaluate the relationship between time delay and human factors during construction work. This paper contributes to exploring the signal latency by long-distance teleoperation and assesses its impacts on work performance, task load, and behavior changes while performing construction tasks.

## INTRODUCTION

With the advanced technology in teleoperation, operating long-distance teleoperated robots have become feasible. NASA plans to build a sustainable habitat on the Moon's surface to explore Mars through the Artemis Program. To build a habitat on the lunar surface, construction tasks such as surveying, excavation, and site preparation should be conducted considering extreme environments (i.e., microgravity, regolith dust, extreme weather, etc.). Under those inherent environmental constraints, teleoperated robots that allow for human-robot interaction will play a key role in the success of extraterritorial construction. However, the time delay is a critical problem that inevitably occurs in data processing or signal transmission in the long-distance teleoperated system.

In this context, time delay (i.e., end-to-end latency) can be defined as the delay between input action and visible output response (Chen et al. 2006). Time delay is usually caused by the transmission of information across a communication network. Current technology has limitations in lowering the latency that is related to communication availability, bandwidth, and latency impact productivity (Wilde et al. 2015). As such, there are challenges in teleoperation and human-robot interaction. Operator fatigue and cognitive overload can cause poor decisionmaking or human errors (Lee et al. 2022), and operators' behaviors are greatly affected by the work environment and interactions (Liu et al. 2022). Reducing latency impact can enhance human capabilities by enabling operators to be telepresent and supporting situational awareness during work.

Construction tasks have unique characteristics conducted in unstructured environments. Also, many tasks require immediate situational awareness and decisions based on skills and knowledge in dynamic and complex conditions. Therefore, human interaction with the teleoperation robot within time delay conditions will affect the operator's work performance, task load, and behaviors. This study is aimed to assess and validate the effects of a teleoperator's task performance, mental workload, and behavior change in different time-delay conditions of construction tasks to explore human interaction in delayed time.

## RESEARCH BACKGROUND

**Teleoperation with time delay:** Prior studies have revealed that operators' task performances were degraded in the time delay condition, and the mental workload was increased. In a recent study by Timman et al. (2023), which is about the time delay effect in teleoperation between Earth and space, they tested the hypothesis that an increased time delay would lead to a higher perceived workload and lower human performance in human-robotic integrated operations. For exploring human-robot interaction under time delay conditions in a lunar teleoperations sample task, the time delay of the operated rover was determined by the distance from the lunar surface (no delay), lunar gateway (0.5s), and Earth (3s). A study that used a student-built teleoperated rover by Burns et al. (2019) conducted an experiment to lay the groundwork for remote rovers on the Moon by astronauts aboard the LOP-G (Lunar Orbital Platform-Gateway). Focusing on monitoring the mental workload, Guo et al. (2022) evaluated the impact by investigating two significant confounding factors, which are time pressure and latency, on space teleoperation. From previous studies, we found that time delays impact operators' mental workload for extraterrestrial teleoperation tasks. Although teleoperation studies with latency have been performed in other domains, such as teleoperated surgical robots and astronaut-robots, there is a dearth of experimental studies in construction contexts. Using joysticks for teleoperation tasks of extraterrestrial construction needs to be explored in a different way compared to other domains' perspectives since the operators should interact with unique challenges such as invisible underground and unstructured environments. This study explores the operators' mental workload and performance for teleoperated operation for construction tasks during time-delayed communication.

**Mental workload in time-delayed teleoperation.** For measuring the impact of time delay, subjective (NASA task load index), objective data related to performance (i.e., completion time), and physiological data (i.e., eye movement, electrodermal activity (EDA)) allow factor-induced mental workload estimation and performance evaluation in tasks. NASA task load index (TLX) (Hart and Staveland 1988) is a well-known tool for measuring task load to assess subjective mental workload. Participants can determine the mental workload rates across six dimensions of their performance.

Eye-tracking data such as eye gaze point and blink in teleoperation were generally associated with visual processing and information acquisition (Martinez-Marquez et al. 2021). Martinez-Marquez et al. (2021) explored applications of eye-tracking technology in high-risk industries: aviation, maritime, and construction. Blink duration involves a correlation with respect to mental workload. However, the results of physiological measures in mental workload related to blink rate were mixed, showing increasing rates but sometimes decreasing rates depending on the visual demands (Marquart et al. 2015). Researchers found a decrease in the eye blink rate for more visually demanding tasks compared to less visually demanding tasks (Marquart et al. 2015). Blink rate can be interpreted considering the compounded factor of mental workload and visual demands. Eye-tracking data has been used in medical surgery as well as aviation to improve task strategies and trainee performance. As such, there is a potential for eye-tracking data that can be used to assess mental workload, immersion level, and user experiences within various VR environments (Li et al. 2021).

Meanwhile, as another physiological data, electrodermal activity (EDA) measures changes in the skin's resistance to an electrical current that allows observing the autonomic nervous system since the sympathetic nervous system innervates the sweat glands (Choi et al. 2019). In the construction contexts, Choi et al. (2019) studied stress reactivity and found that more EDA peaks are detected during stressful situations than during non-stressful situations. EDA data are capable of use in representing physiological responses from operators, providing the stress level and mental workload while performing tasks.

## Work Performance, Task Load, and Behavior Changes in Time-Delayed Teleoperation Tasks in Space Construction

**Participants.** For this study, 12 participants (mean age = 23.8 years, *SD* = 3.2, 10 males and 2 females) were recruited. All participants were Texas A&M students (3 undergraduate and 9 graduate) and were engineering-related majors of various departments. They had a normal or corrected-to-normal vision. The levels of participants' VR experiences and joystick controller familiarity were varied.

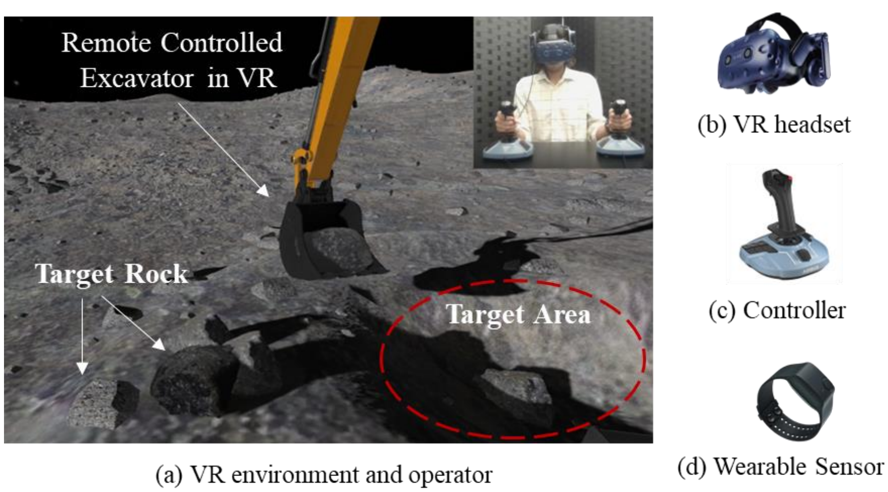


**Figure 1. Experimental setups**

**Materials.** The experimental task was to move rocks to the target area on the moon's surface in virtual reality (VR) environments. For the VR modeling, the simulation environments were developed in Unity with a head-mounted display (VIVE pro) and ambidextrous joysticks as the controller (Figure 1). Participants took on the wearable sensor (Empatica E4), which allowed for collecting physiological data while performing the tasks.

**Experimental design and tasks.** To assess work performance, task load, and behavior changes in delayed conditions for construction tasks, we modeled three scenarios with different levels of time delay: no-delay, 1.5s, and 3s delay conditions. The selected time delay was designed: 1.5s taking account of the range of orbiting spacecraft on low earth orbit or lunar gateway, and 3s for the Earth ground to Moon-base teleoperation system. Figure 2 presents the conceptual teleoperation system on the lunar surface construction site.

All participants conducted given tasks in three different time-delayed conditions, which emulated excavation tasks for site preparation phase in the lunar construction. The subjects were asked to move three rocks to the targeted area by manipulating the joysticks (Figure 1). The participants used the mechanism of the joystick operation of an excavator controller, which can operate the movement of a vehicle body, stick, boom, and bucket. This task is associated with removing rocks and obstacles on the site in the early phase of lunar construction. Participants finish the session when they move three rocks to the target area. We limited the time for each session to a maximum of 10 minutes to prevent participant fatigue and any cumulative effect. There were no auditory effects in all virtual environments.

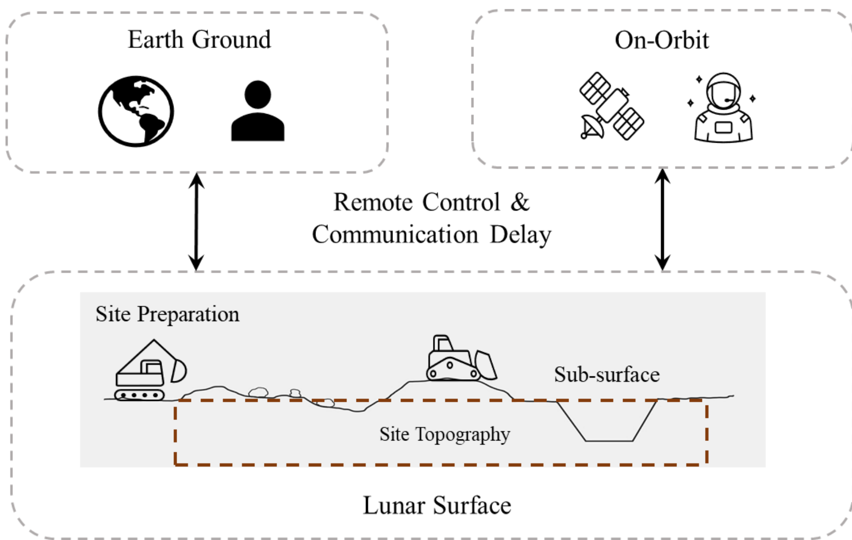


**Figure 2. Teleoperation system and site preparation tasks on the lunar surface. The distance from the Earth and on-orbit to the lunar surface affects communication delay.**

**Experimental procedures.** The practice session was designed to allow to familiarize the participants with the joysticks and VR environments, along with wearing a head-mounted display before starting the task sessions. Before operating the space excavator in three conditions, the training and exercise were conducted until the participants successfully moved a rock to the target area to practice the joystick operation and understand the tasks. The session of no delay condition was given to all participants to perform as the first order, and the second session and third were given randomly as 1.5s or 3s delay. All procedures, including the introduction of experiments, practice training, three session tasks, surveys, and interview, took between 30 and 45 minutes, depending on the participants' performance time.

**Measurement.** Multiple measurement approaches, including objective and subjective metrics, assessed operators' work performance, task workload, and behavior changes for each time-delayed condition.

***a) Work performance (completion time and first accomplishment time)***

Task completion times and the first successful movement of one rock were measured for each session to compare the impact of different delayed conditions. We measured the completion time for every three conditions with a limited time of 10 minutes. Also, we examined the first accomplishment time of moving rock to the target area to compare the performance in different delay conditions.

***b) Task workload (NASA TLX)***

Participants reported NASA-TLX (Hart and Staveland 1988) rates that were intended to measure the operator's perceived workload along six dimensions: mental demand, physical demand, temporal demand, effort, own performance, and frustration. We calculated their scores on an interval scale ranging from low (1) to high (20) for six dimensions. NASA-TLX provides subjective ratings of workload immediately following each task session.

***c) Questionnaires for VR experiments***

Regarding VR experiences, participants answered three questions: simulator sickness symptoms, VR immersiveness, and joystick operating satisfaction on the feeling. Simulator sickness symptoms listed up allowing to mark within 16 symptoms based on the previous simulator sickness questionnaire (SSQ) study (Kennedy et al. 1993). Also, the subjects answered the experience extent of VR immersiveness and joystick controllers within 5 Likert's scale, which ranged from bad to excellent.

***d) Eye tracking data (fixation, saccade, and blink rate)***

Given the benefit of eye-tracking-based studies in immersive virtual reality (Li et al. 2021), we assessed eye blink rate, fixation, and saccade data for this study. Blink rate (blinks per minute) was derived from the total number of eye blink events that took place in each participant's session stimuli time.

***e) Psychophysiological data (EDA)***

EDA refers to an autonomic change in the electronic properties of the skin in response to sweat secretion. We assessed EDA data to find the relationship between human factors while conducting the given tasks. Participants' physiological data were collected using a wearable sensor (E4 wristband) while conducting tasks.

## RESULTS AND DISCUSSIONS

**Task performance and completion time.** Prior studies examined that latency led to performance degradation in teleoperation through empirical research. As a result of this experiment, we validated delayed time conditions in the context of construction, which led to lower performance. This study found a significant impact on the completion time. The impact could be larger if there were no limited time given for each session. To compare the impact of different conditions, we conducted one-way ANOVA with task completion time in three different conditions as the dependent variable with three different levels of delayed time (i.e., 0, 1.5, and 3s delay). The average time of each task session completion and the first accomplishment for moving rocks to the target area significantly differed in time-delayed conditions (Figure 3).

Only 4 subjects (33%) successfully completed all three sessions of moving three rocks to the target area within a given time (maximum 10 minutes for each session). In the no-delay session and 1.5s delay, 10 and 9 participants succeeded in the task within the limited time, respectively. In the 3s delay session, only 5 subjects (42%) succeeded in the task in time. One participant failed all sessions due to a lack of joystick operation skills, and we excluded the participant's data from the performance evaluation analysis.

Operators' completion time and the first accomplishment time to move a rock to the target area are related to the visual response time and control errors while manipulating the excavator's bucket, stick, boom, and cabin movement. When latency is detected, operators change their behavior to a "move and wait" strategy (Sheridan 1993). We observed similar behavior changes from our participants and found their changed manipulation behaviors and strategies in delayed sessions. We provided an open-ended question after the completion of experimental sessions that we asked how the participant change his/her behaviors or operations in delayed conditions. As adapted to the latency, the operators' manipulation speed became slow based on the response time of visual information on the display. They described their behavior changes in the form of "adapted or adjust," "wait," "stop (or without moving)," and others ("calibrated," "slow movement," "think," and "reevaluate"). All participants could clearly recognize the differentiation within three sessions and answered that they affected performance and behaviors in time-delayed conditions.

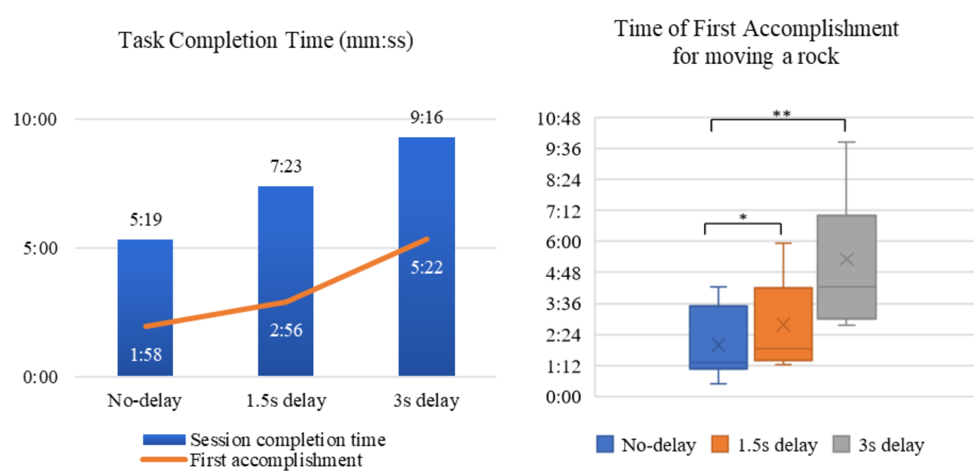


**Figure 3. Work performance. Left: task completion time in three different delay conditions. Right: comparison of first accomplishment time of moving rock to target area. *Note*. $^{*}p < .05$. $^{**}p < .01$.**

**Task load index for tasks with time delay.** NASA TLX has been used as one of the tools for measuring a task load in time-delayed teleoperation studies. Prior studies found an increase in the task load scores when latency increased (Timman et al. 2023; Wilde et al. 2015). In this study, we validated that all means of scores in NASA TLX questions were increased as the time delay increased. Furthermore, we carried out a one-way ANOVA; the significance level was set at 0.05 for statistical analyses for this study. As a result of statistical analysis, it turned out that ANOVA represents the feature with statistically significant differences ($p < .05$) with respect to no-delay versus 3s delay conditions at the mean of total score (no-delay = 44.8, 3s = 70.3, $p$ = .28), mental demand (no-delay = 8.8, 3s = 14.3, $p$ = .015), and frustration (no-delay = 5.6, 3s = 11.8, $p$ = .005) (Figure 4). The mental demand and frustration through the interview also described the participants' feelings well. They reported their mental workload and feelings in words such as "difficulty in joysticks," "frustration," "need patience," and "mistakes" after completing all experimental sessions.

**Eye tracking in time-delayed teleoperation.** Blinks and eye movements are sensitive to visual information processing and mental workload. Fixations and saccades increase in general when mental workload and visual information are increased. However, the correlations between task load and eye movement data could vary depending on the task characteristics. For example, the blink rate on mental workload is shown as mixed results by presenting either increasing or sometimes decreasing rates associated with the visual demands (Marquart et al. 2015).

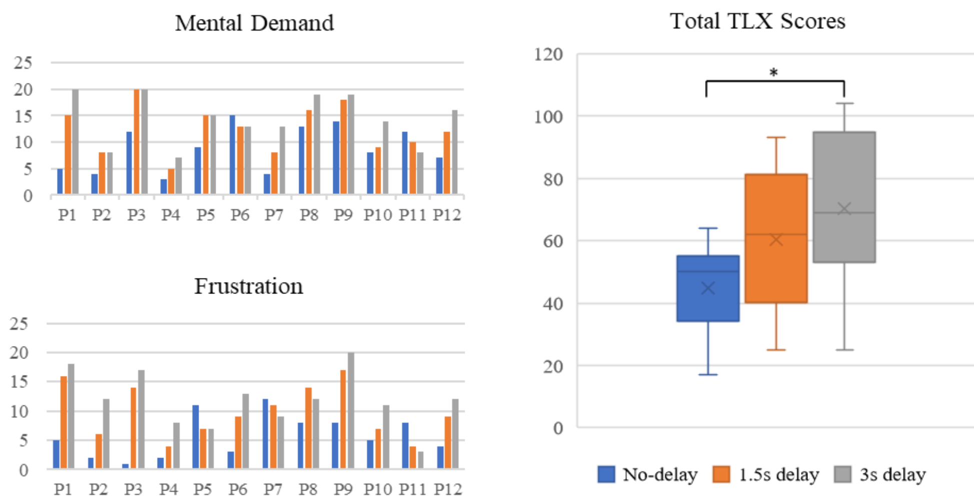


**Figure 4. Task load. Left: mental demand and frustration scores of each participant in three conditions. Right: mean of total scores comparison. *Note.* $^{*}p < .05$.**

***a) Blink rate***

As a result of the experimental study, it turned out there was a difference in average, and the mean blink per minute for each session (no-delay = 13.5, 1.5s = 16.4, 3s = 21.6) increased when the time delay increased (Figure 5). However, there was no significant ($p = .21$) blink per minute between three sessions with this sample size and experiment. Results of the mean of each group showed that blink frequency increased in the 3s time-delayed condition, which infers that the mental workload could affect the blink rate. However, there are limitations to conducting statistical analysis since the size of the sample is relatively small. For more validation, there is a need for large sample size for analysis in the future.

***b) Eye movement (fixation and saccade)***

As a result of examining the relationship between eye movement measurements in three conditions, there was no significant association in fixation between groups in this study. In saccades, the mean number of saccades per minute between groups (no-delay = 9.6, 1.5s = 8.4, 3s = 7.6) showed a significant difference between groups (Figure 5). The results indicated that the means of the number of eye movements was significantly decreased in time-delayed conditions even though there were significant increases in the task load. This is somehow opposite to the conventional trend that eye movements tend to increase when the mental workload increases. This implies that eye-tracking data in the context of mental workload in time-delayed conditions need to be evaluated carefully. We found that time delayed environment could affect workloads differently compared to other work environments that focused on visual information processing and its impact on task difficulties.

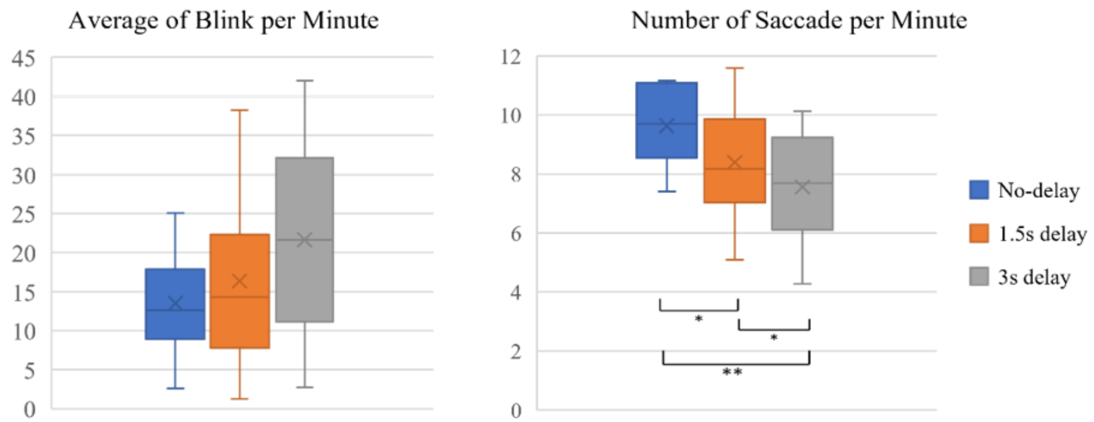


**Figure 5. Eye movement comparison (*n*=11). Left: number of blinks per minute. Right: number of saccades per minute. *Note.* $^{*}p < .05$. $^{**}p < .01$.**

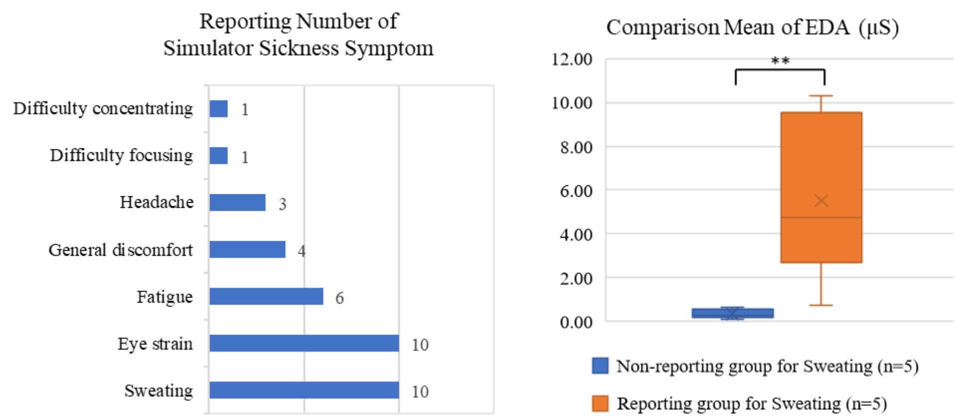


**Figure 6. Simulator sickness symptoms. Left: reported simulator sickness symptoms and the numbers. Right: EDA comparison between non-reporting and reporting group for sweating. *Note.* $^{**}p < .01$.**

**VR experience in time delayed teleoperation.** Participants were asked to report simulator sickness symptoms on the questionnaire sheet if they had any symptoms after each session. 2 participants had shown none, and the others reported at least one symptom while conducting three sessions (Figure 6). Seven symptoms were reported among 16 typical symptoms. Sweating and eye strain were the most frequently reported symptoms.

When it comes to EDA data analysis for observing physiological changes, 10 participants' data were used by excepting two participants' data since one did not have measurable accomplishment and the other obtained discontinued EDA data. We found that the group who reported sweating (mean = 5.51 μS, *SD* = 4.1) had saliently larger figures of EDA compared to the non-reporting group (mean = 0.33, *SD* = 0.33). This indicates that participants' physiological data clearly supports the reliability of self-reported data. Interestingly, four participants who successfully completed three sessions reported sweating symptoms. Even though the sample size was relatively small, it was observed that the sweating symptom had shown a strong correlation with task completion success in this study. We examined that the EDA could be correlated with their feeling and simulator sickness symptoms. EDA will be applicable to evaluate stress, mental workload, simulator sickness, etc., while performing teleoperation tasks. There were no significant differences in simulator sickness symptoms between no-delay and delayed sessions in this scenario. Overall, VR immersion and satisfactory operation on controllers decreased from 4.3 scores to 3.7 and 4.2 to 3.3 from no-delay to 3s delay session based on the 5-point Likert scale questions.

## CONCLUSION

Teleoperation is essential for extraterrestrial construction but is a challenging task. While eventually fully autonomous robot systems will be adopted to planetary habitats, human-robot interaction is important to support stable and accurate telerobotic systems to perform construction tasks. To contribute to the human-robot interaction knowledge in long-distance telerobotic systems, we performed VR experiments for teleoperated construction tasks in time-delayed conditions to explore human operators' performance, task load, and behavior changes. The time delay is a critical problem impacting human operators' performance and abilities between human and robot interaction. In the experimental study, we validated the performance degradation and operator's workload increase based on subjective and objective measurement metrics. We also found that operators tended to change their teleoperating strategies under delayed conditions. Physiological data such as EDA and eye tracking data have been analyzed to understand human operators' performance, task load, and subjective answers on simulation symptoms. Eye-tracking still needs further investigation in time-delayed teleoperation environments. Future research will consider assisted feedback for improving performance in time-delayed conditions. We expect this research will contribute to how to train effectively and reduce the impact of the delayed condition by enhancing the VR environment and interfaces. In this experimental study, we had limitations since there was a small sample size, and it was difficult taking into account subjects' different levels of fatigue or awareness conditions and confounding factors. Each element should be explored thoroughly with experimental studies. The lessons learned from this study will feed forward to future teleoperated construction tasks in time delay.

## ACKNOWLEDGEMENT

This material is in part based upon work supported by the National Science Foundation (NSF) under Award #2221436. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

## REFERENCES

Burns, J. O., Mellinkoff, B., Spydell, M., Fong, T., Kring, D. A., Pratt, W. D., Cichan, T., and Edwards, C. M. (2019). “Science on the lunar surface facilitated by low latency telerobotics from a Lunar Orbital Platform - Gateway.” *Acta Astronautica*, 154, 195-203.

Chen, J. Y. C., Haas, E. C., Pillalamarri, K., and Jacobson, C. N. (2006). *Human-Robot Interface: Issues in operator performance, interface design, and technologies*. Army Research Laboratory, 100.

Choi, B., Jebelli, H., and Lee, S. (2019). "Feasibility analysis of electrodermal activity (EDA) acquired from wearable sensors to assess construction workers' perceived risk." *Safety Science*, 115, 110-120.

Guo, Y., Freer, D., Deligianni, F., and Yang, G. Z. (2022). "Eye-tracking for performance evaluation and workload estimation in space telerobotic training." *IEEE Transactions on Human-Machine Systems*, 52(1), 1-11.

Hart, S. G., and Staveland, L. E. (1988). "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research." In *Advances in Psychology*, 52, 139-183. Elsevier.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). "Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness." *The International Journal of Aviation Psychology*, 3(3), 203-220.

Lee, J. S., Ham, Y., Park, H., and Kim, J. (2022). "Challenges, tasks, and opportunities in teleoperation of excavator toward human-in-the-loop construction automation." *Automation in Construction*, 135, 104-119.

Li, F., Lee, C.-H., Feng, S., Trappey, A., and Gilani, F. (2021). "Prospective on eye-tracking-based studies in immersive virtual reality." *2021 IEEE 24th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*, 861-866.

Liu, D., Ham, Y., Kim, J., and Park, H. (2022). "Towards a collaborative future in construction robotics: A human-centered study in a multi-user immersive operation and communication system for excavation." *Proceedings of the 1st Future of Construction Workshop at the International Conference on Robotics and Automation (ICRA 2022)*. ICRA 2022 Future of Construction Workshop.

Marquart, G., Cabrall, C., and de Winter, J. (2015). "Review of eye-related measures of drivers' mental workload." *Procedia Manufacturing*, 3, 2854-2861.

Martinez-Marquez, D., Pingali, S., Panuwatwanich, K., Stewart, R. A., and Mohamed, S. (2021). "Application of eye tracking technology in aviation, maritime, and construction industries: A systematic review." *Sensors*, 21(13), 4289.

Sheridan, T. B. 1993. "Space teleoperation through time delay: Review and prognosis." *IEEE Transactions on Robotics and Automation*, 9(5), 592-606.

Timman, S., Landgraf, M., Haskamp, C., Lizy-Destrez, S., and Dehais, F. (2023). "Effect of time-delay on lunar sampling tele-operations: Evidences from cardiac, ocular and behavioral measures." *Applied Ergonomics*, 107, 103910.

Wilde, M., Harder, J. T., Ventura, J., Hörmann, J., and Walter, U. (2015). "Impact of space-to-ground video transmission constraints on teleoperated final approach and docking." *Journal of Aerospace Information Systems*, 12(7), 441-454.