The effect of challenging work environment on human-robot interaction and cognitive load during teleoperation: a case study of teleoperated excavator in a virtual experiment*

Jin Sol Lee, and Youngjib Ham

Abstract— **Construction sites typically involve a risky, dynamic, and challenging work environment. Despite numerous safety training programs and regulations, accidents still occur in construction sites, especially when working with construction robotics. To alleviate this problem in the most fundamental way, teleoperation that allows operators to work remotely has been studied. Teleoperated construction robots have the great potential to be used in various contexts for extreme and hazardous construction sites. Here, work conditions for human-robot interaction in construction differ from those in other structured and controlled environments like manufacturing factories, and thus there is a need for the associated studies. In this paper, we aim to measure and analyze the performance of human-robot interaction and the cognitive load of human operators in dynamic and challenging construction work environments (hazardous risks such as underground utility strikes and working under time constraints).**

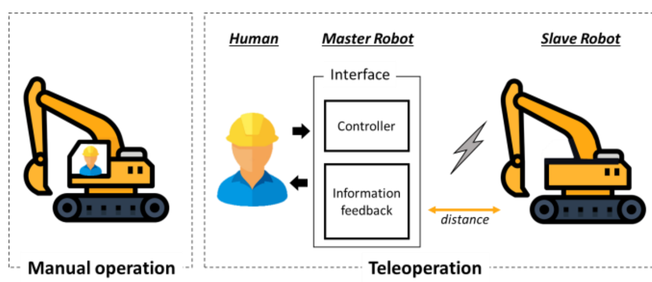
I. Introduction

The construction site is known as a dynamic and challenging environment. Especially, construction excavation task has a high probability of fatal injuries and damages in the event of an accident [1]. Especially if a utility strike occurs during excavation, not only is damage and cost increased, but also the supply of water, gas, electricity, and commutation cable that is vital to people's everyday lives is negatively affected [1]. Despite the significance, it is not trivial to avoid these on construction sites. Providing a safe work environment for earthwork while reducing accidents is essential.

There has been increasing interest in automation in hazardous construction workplaces. Even with the most advanced technologies, achieving full autonomy for construction tasks still requires a great deal more research and development due to the extremely dynamic, complicated, and uncertain nature of construction jobs, as compared to manufacturing [2]. As a result, teleoperated construction robots have been studied in various contexts and become a promising solution for extreme and hazardous construction sites [3]. Teleoperation means operating a slave robot via a master robot by a human operator from a distance as illustrated in Fig. 1 [2]. Since the human operator cooperates with the robot system as a commander and takes advantage of human-robot interactions, it has a wide range of capabilities and potential as a robotic application for construction tasks such as excavation [2].

Compared to a controlled and structured work environment (e.g., manufacturing), teleoperation in construction is typically obscured by open and changing environments [2]. These include dynamic flows of construction tasks, various work types, and different work and site conditions such as weather, soil conditions, and construction equipment that vary from site to site. Manually operating a construction robot by onboarding enables the human operator to directly sense and respond to the environment in which the robot is situated, whereas remotely operating a robot requires information feedback and awareness of the distanced situation via an interface, which can be a demanding job for the operators as illustrated in Fig. 1 [1]. In this regard, there is a need to carefully examine how the human operator's cognitive load and performance could be affected by challenging environments of construction sites in terms of human-robot interaction. This paper aims to investigate how the challenging work environments (e.g., hazardous risks such as underground utility strikes and work under time pressure) affect human-robot interaction during teleoperation situations in construction.

Figure 1. Teleoperation and human-robot interaction



This paper is organized as follows. In Section II, we look at relevant prior studies regarding human-robot interaction in challenging work environments in the construction domain and other disciplines. Section III and IV show the process and the results of the virtual experiments to explore the effect of the challenging work environment on human-robot interaction

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in construction. In Section V, we summarized the preliminary outcomes of the proposed studies and discuss the possibilities and the impact of our work.

II. Literature Review

A. Theoretical background

According to the Adaptive Decision Maker theory, human decision behavior is determined by an individual considering various task conditions or environments [4]. In other words, even if the same person performs the same task, the final decision or behavior may change if the task condition or environment is different. Decision-makers try to balance their effort with the accuracy of performance by considering multiple task constraints [5]. Depending on the level of difficulty of these task conditions, stress or cognitive load increases when people perform a task, which affects the decision and performance in the course of the task. However, an increase in stress or cognitive load does not necessarily imply a decrease in performance or decision quality. According to the Yerkes-Dodson Law, task performance is an inverted U-shaped function of attention [6]. In other words, the performance level may increase as the arousal level go up, and it drops after reaching the fatigue point. Thus, in order to achieve the most optimal human performance and minimize the risk of injury and task failure during excavation, the operator's attention needs to be managed within a certain range in a challenging environment.

B. Task performance under time pressure

Time pressure is one of the major stresses that affect decision-making, behavior, and task performance [7], and make the work environment more challenging. There have been studies regarding time pressure in various disciplines such as the automotive and aviation industry to understand the performance and cognitive load of drivers and pilots. Time pressure may cause excessive stress, productivity demands, negative emotional reactions, anger, and aggressive performance [8], [9]. This would lead to risk-taking behaviors or decisions to achieve goals in time, just like a driver may not be able to pay close attention to their surroundings and neglect safety when speeding [8]. In contrast, when the appropriate amount of time pressure is applied, it can enable an individual to work optimally, as well as have positive emotions, and increase job satisfaction [10]. Time pressure has become a routine phenomenon in construction by site managers or clients or by unexpected risks such as weather. There have been studies on time pressure in the construction industry. Under time pressure, some researchers looked at the electrical line workers' risk-taking behavior and cognitive demand [11], and others conducted experiments in a virtual reality environment to find how time pressure affects the hazard recognition, analysis, and decision making of construction site workers [5].

Since operators play a significant role in efficient construction robot manipulation [12], our study examines how time pressure affects human-robot interaction performance and cognitive load in teleoperation when conducting hazardous construction tasks and how these factors correlate with each other.

III. Methodology

Experimental tasks in this study were designed to understand how human-robot interaction performance and operator's cognitive load change in a dangerous work environment depending on the level of time pressure.

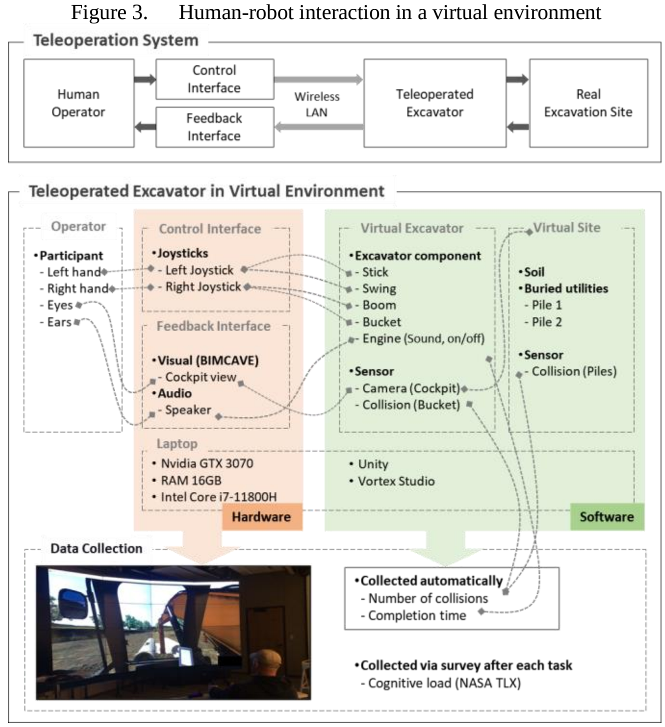
A. Environment design and apparatus

The site scenario in the virtual environment was built upon the site visit of actual construction sites and advice from excavation experts (Fig. 2).

Figure 2. Virtual site scene setup

We developed a challenging site scenario that requires participants to dig the soil delicately while avoiding two hazardous buried utilities. In the experiment, participants manipulated the excavator with two joysticks, the control interfaces of the excavator, while observing the movement of the excavator and the surrounding situation in the computer aided virtual environment (CAVE). During the experiment, performance data of operators were automatically collected (Fig. 3).

Figure 3. Human-robot interaction in a virtual environment



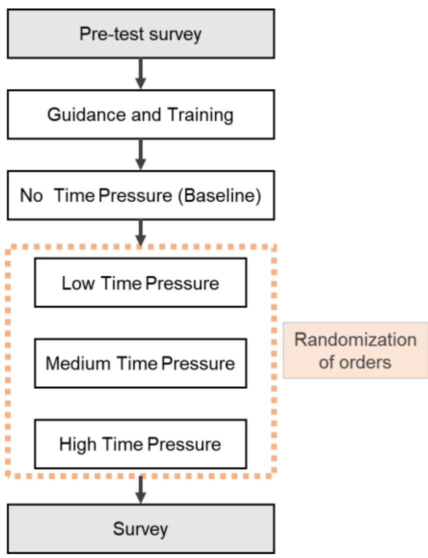
B. Experiment

- *Task description*

In the experimental task, we had participants excavate the soil between two utility lines and dump the soil by swinging the excavator body to the left, repeating a total of 5 times. Each time the soils were dug, participants were asked to fill the bucket with soil as much as possible in the 'Guidance and Training' session. Graduate students majoring in architecture and construction engineering participated in the pilot experiments.

- *Procedure*

Figure 4. Procedure of experiment



Step 1. Pre-test questionnaires (gender, age, 3D game experience, and work experience in the AEC industry) were provided to the participant before the virtual experiment begin.

Step 2. Guidance and training session. Participants were trained not to hit the utilities during their task. Basic excavator control such as arm out/in, swing left/right, boom down/up, curl/uncurl bucket were requested. Only if they succeeded without making a mistake more than 15 times in a row, the participants could move onto the next session so that they could adapt to the basic manipulation as much as possible before the experiment task with time pressure levels.

Step 3. Task experiment session. At first, all participants performed excavation in the absence of time pressure. This measured time with no time pressure (NTP) was used as the reference time when applying the time pressure. In the low time pressure (LTP) task, participants were asked to finish the task at 90 percent of NTP time, 80 percent of NTP time for the medium time pressure (MTP) task, and 70 percent of NTP time for the high time pressure (HTP) task. During the experiments with time pressure, we tried to reduce the learning effect bias by randomizing the orders of time pressure levels for each participant (Fig. 4).

Step 4. After each task, the NASA TLX questionnaire was used to measure the cognitive load depending on the time pressure levels [13].

- *Performance and cognitive load assessment*

Performance related to human-robot interaction in a challenging environment was measured by the number of collisions and completion time. The participants were asked to rate their cognitive load with a 0 to10 scales in six aspects (Mental Demand, Physical Demand, Temporal Demand, Self-rated Performance, Effort, and Frustration level).

IV. Result and Discussion

Given the relatively small number of participants in the pilot study, the mean of the preliminary outcomes may involve an interpretation error due to an outlier or a skewed distribution. Therefore, the analysis of the results was conducted with the median known as a better measure of central tendency rather than the mean.

A. Human-Robot Interaction (HRI) Performance

- *Number of collisions*

The number of collisions is a metric to measure the performance accuracy of manipulation. Collision refers to the case where the bucket of the excavator hit buried utilities during the experiment. Therefore, if the number of collisions is high, it means that more utility strikes have occurred, and in turn it means that the probability of leading to a dangerous accident increase. The smaller the number of collisions means the better human-robot interaction performance. When it comes to analyze the HRI performance depending on the time pressure level with a median value, it was observed that the HRI performance was the highest at low time pressure based on the collision number in the experiment result (Fig. 5). This is consistent with the Yerkes-Dodson Law that appropriate stress or arousal levels may improve performance [6].

Figure 5. Number of collisions under time pressure

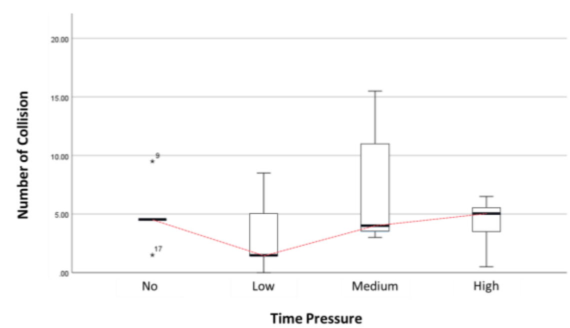
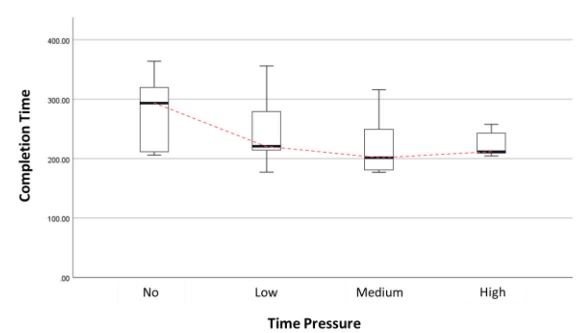


Figure 6. Completion time under time pressure



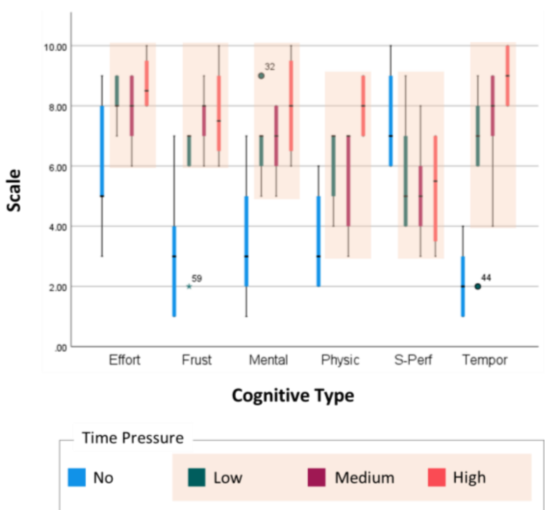
- *Completion time*

The completion time for the given tasks in the presence of time pressure (LTP, MTP, HTP) was relatively lower than that with NTP (Fig. 6). Especially the results of the LTP showed not only an improvement in HRI performance, but also a reduction in completion time in comparison with NTP. The participants in HTP got pressure to complete the task as fast as possible compared to other sessions with time pressure (LTP, MTP), however, it was observed that the completed time between MTP and HTP did not differ significantly (Fig. 6).

B. *Cognitive load of the human operator*

Participants were asked to answer the following questions after each task during the experiment. ***Mental Demand*** - Was the task easy or demanding, simple or complex? ***Physical Demand*** - How much physical activity was required (e.g., pushing, pulling, controlling, manipulating)? ***Temporal Demand*** - How much time pressure did you feel performing the task? ***Self-rated Performance*** - How successful or satisfied did you feel upon the performance or completion of the 0 to 10 given task? ***Effort*** - How hard did you have to work (mentally and physically) to accomplish your level 0 to 10 of performance? ***Frustration Level*** - How insecure, discouraged, stressed, and annoyed versus content, relaxed, and 0 to 10 complacent did you feel during the task? Overall, with time pressure, it was observed that the cognitive load is higher in proceeding with the excavation task near buried utilities compared to without time pressure (Fig. 7).

Figure 7. Cognitive load under time pressure (NASA-TLX)



V. Conclusion

In this study, we investigated how challenging work environments in construction sites (hazardous safety risks such as underground utilities and time pressures) affect human-robot interactions and the cognitive load of human operators during teleoperation. Such a challenging environment is a work environment frequently encountered by construction workers in the case of excavation. In particular, most of the safety accidents related to construction are accidents caused by less-skilled workers with less than 2 years of work experience in construction. Accordingly, in this study, human-robot interaction performance and cognitive load of novice operators were primarily investigated the case of teleoperation in a challenging environment in a virtual environment. Overall experiments show that the challenging work environment with time pressure increases the individual's cognitive load and lowers the performance compared to working under no time pressure. Interestingly, the performance related to human-robot interaction has been improved given a reasonable time pressure (low time pressure). Therefore, for future research, it is necessary to conduct more in-depth studies taking into account the risk of the task, the difficulty of the task, and the different levels of time pressure. By doing so, we anticipate that this research will significantly contribute to the body of knowledge for human-robot interaction in a challenging environment during teleoperation.

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