Factors Leading to Reduced Construction Productivity in Unmanned Construction

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Abstract -

This study investigates factors affecting construction productivity in unmanned construction, a method developed in Japan for safely conducting recovery operations post-disaster using remotely operated machinery. Despite its widespread adoption, unmanned construction is typically less productivity than conventional methods. This research aims to identify and quantify the factors of this reduced productivity. Experiments were conducted using a hydraulic excavator in various operation environments, from manned to remote, focusing on visual information, operation interface, sensory information, and image display. The results reveal that the main factors decreasing productivity are differences in visual information for situational awareness and operating interface, with the former having a greater impact. Sensory information and image display differences were found not to be major contributors. The findings are specific to tasks similar to the model task used in the study and suggest the need for further research under various construction conditions to enhance productivity in unmanned construction, which is vital for disaster response and regular construction site productivity.

Keywords -

unmanned construction; remote control; construction equipment; working productivity

1 Introduction

Japan has experienced numerous disasters, including landslides due to heavy rain, earthquakes, and volcanic disasters. Recovery construction work post-disaster often takes place in areas at risk of secondary disasters. To safely conduct these recovery operations, a construction method has been developed using remotely operated construction machinery, allowing operators to work from a safe distance as shown in Figure 1. This method, known as "unmanned construction," was uniquely developed in Japan[1]. It was first introduced during the emergency recovery work of the Joganji River in 1969 and significantly evolved following the "Unzen Fugen Volcano Unmanned Construction Test Work" started in 1993[2]. Since then, it has been established as a practical construction method and adopted in various disaster sites, including the Usu Volcano eruption, the Niigata Chuetsu Earthquake, the Great East Japan Earthquake, the Kii Peninsula large-scale landslide disaster, and the Kumamoto Earthquake, with nearly 200 cases of implementation domestically[3][4].

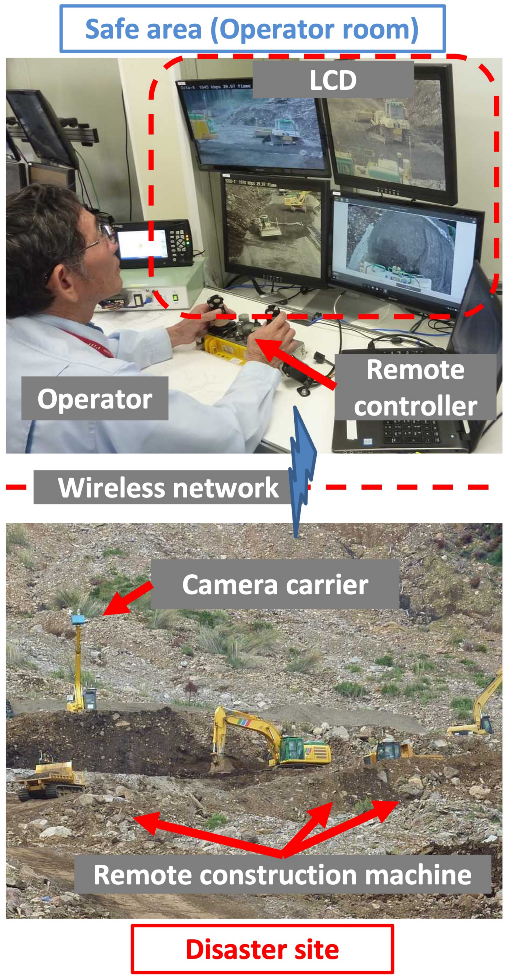


Figure 1. Overview of Remote Operation System

However, it is generally said that unmanned construction is less productivity compared to conventional con-

Table 1. Examples of Factors Leading to Reduced Construction Productivity in Previous Studies

Factors Identified in Previous Studies	Classification in This Study
Delay in camera footage Insufficient resolution of camera footage Lack of depth perception in camera footage Insufficient camera angle	1) Visual Difference
Short control levers Different response of control levers	2) Operation I/F Difference
Different feedback in terms of sound and vibration	3) Sensory Information Difference

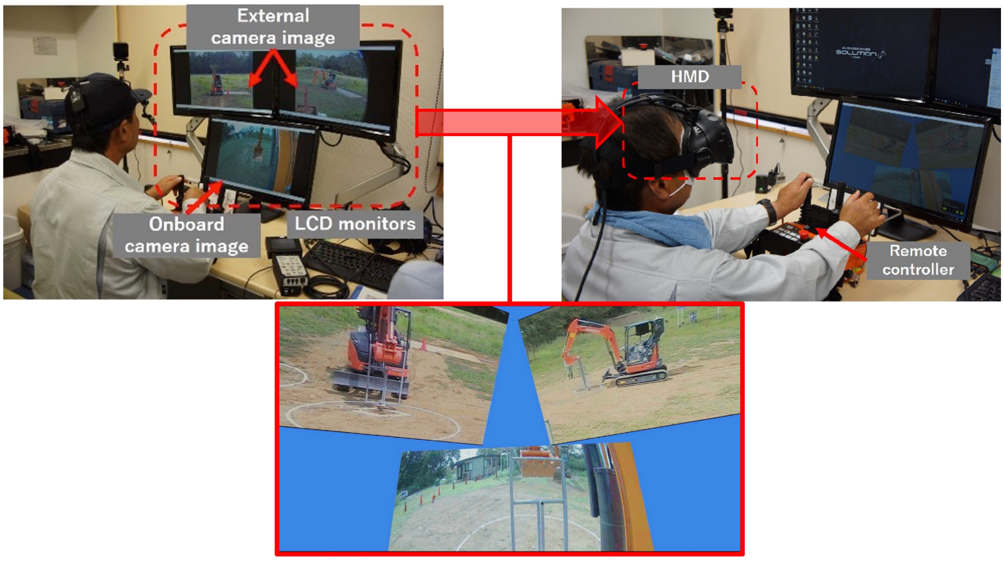


Figure 2. Visual System for Remote Operation. Left image shows conventional remote operation system using LCD, and Right image shows HMD based remote operation system

struction methods. Quantitative studies[5][6] have shown that the productivity of remote operation is about 45% of that during manned operation. To promote the adoption of unmanned construction and complete disaster recovery work safely and swiftly, it is necessary to improve the productivity of unmanned construction.

To improve construction productivity, it is essential to clearly identify the factors of productivity reduction in unmanned construction and focus resources on research and development to address these factors. However, while there are examples of identifying factors of productivity reduction through operator interviews[7], no study has quantitatively verified these factors. Therefore, this study aims to identify the factors of reduced productivity during unmanned construction by conducting experiments using actual remotely operated construction machinery.

2 Factors Analysis Based on Previous Studies

The reason for lower productivity in remote operation compared to manned operation is believed to be due to the operator working in a different environment than during manned operation. The current standard remote operation in unmanned construction, as shown in Figure 1, is conducted inside a control room using a joystick controller for remote operation. The operator watches multiple displays showing footage from cameras mounted on the construction machinery (hereafter referred to as onboard cameras) and cameras installed at positions that provide an overall view of the work area (hereafter referred to as external cameras). Therefore, the differences between manned and remote operation can be broadly divided into the following three points:

1) **Visual difference for situational awareness**
   In manned operations, situational awareness is obtained by the operator through direct visual observation from their seat inside the construction machinery. In remote operations, situational awareness is achieved by monitoring footage from both onboard and external cameras.

2) **Difference in operation interface (hereafter referred to as operation I/F)**

(a) Joystick (b) Seat-type remote controller

Figure 3. Operation Device for Remote Operation System

In manned operations, the operation is carried out using control levers located in the operator's seat within the construction machinery. In remote operations, the operation is conducted through a joystick controller designed for remote control.

3) **Difference in sensory information**
In manned operations, the operator can perceive sensory information such as the tilt of the machine, vibrations, and engine noise. In remote operations, this kind of sensory information is not available to the operator.

Previous studies[5][8][9][10][11] have identified various factors leading to reduced construction productivity. Representative factors are listed in Table 1 and classified into the above 1) to 3) categories.

In this experiment, we attempted to identify which of these differences contribute most to the reduction in construction productivity by gradually changing each of these differences from a manned operation environment to a remote operation environment and comparing the completion times of the same tasks under each condition.

3 Experiment Design

The experiment used a 12t hydraulic excavator capable of remote operation. The target environment for remote operation was set to be similar to the general unmanned construction environment shown in Figure 2.

To clearly identify the factors affecting construction productivity when changing the operation environment from manned to remote operation, it is important to minimize each change (for example, only change the operation I/F). Therefore, in this experiment, we utilized the HMD system developed in [12]) and the driver's seat-type remote controller developed in [13]) to minimize each change. HMD system is designed to replicate the visual setup of the three LCD monitors as shown in Figure 2. The driver's seat-type remote controller is composed of the same driver's seat and control levers as those of the hydraulic excavator, allowing for remote operation using these components as shown in

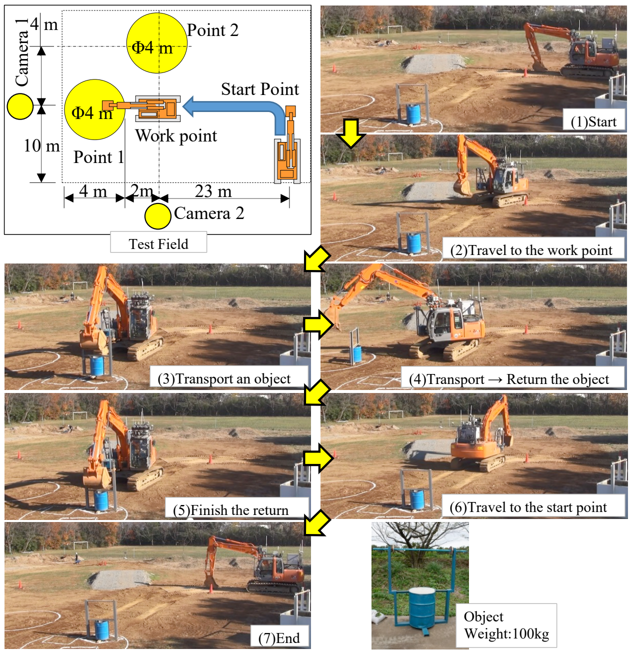


Figure 4. Outline of Model Task II[5]

Figure 3. Table 2 shows the patterns of changes in experimental condition. By utilizing the HMD and driver's seat-type remote controller, we created experimental condition changes in addition to the aforementioned 1) to 3) differences, including differences in image display.

Table 3 lists the equipment used in the experiment other than operation devices. The equipment and system used in the current standard unmanned construction are almost equivalent to those listed in Table 3, making it possible to understand the current factors of productivity reduction in unmanned construction through this experiment. However, as the HMD may be difficult to measure for some operators, as mentioned later, the experiment was conducted with caution.

The operators' age and work experience who participated in the experiment are listed in Table 4. The purpose of this study is to understand the factors of productivity reduction when operators with no experience in unmanned construction perform such operations for the first time. Therefore, we selected four operators who regularly operate hydraulic excavators but have no experience in unmanned construction. The lever operation patterns for manned operation, joystick and driver's seat-type controller were set to the commonly used patterns by all operators. The tasks performed under each pattern were based on the Model Task II[5] as shown in Figure 4, which involves a series of tasks using a hydraulic excavator, including traveling, moving objects, and replacing objects. Operators practiced this model task twice and performed it five times for a total of seven times under each pattern,

Table 2. Experiment Pattern

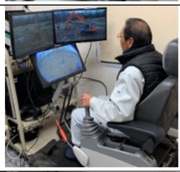
Pattern	Overview	Operation device	Vision device	Bodily sensation
a		Cabin Seat Controller	Direct View	Enable
b		Cabin Seat Controller	Footage by HMD	Enable
c		Seat-type Remote Controller	Footage by HMD	Disable
d		Seat-type Remote Controller	Footage by LCD	Disable
e		Joystick	Footage by LCD	Disable

Table 3. Equipments

Device	Model
Hydraulic excavator	Hitachi ZX120
Onboard camera	AXIS Q1615-MKII
External camera	AXIS Q6155-E
LCD Monitor	iiyama X2382HS
HMD	HTC Vive

Table 4. Operator Information

Operator	Age	Experience (year)
A	49	24
B	64	30
C	65	20
D	64	44

and the completion time of the task (hereafter referred to as cycle-time) was measured.

4 Experiment Result

Table 5 shows the average of five cycle times under each experimental pattern. Since there are differences in cycle times among operators, the data is presented as a percentage of the average cycle time of five runs under experimental pattern a (manned operation), referred to as the cycle time ratio, shown in Figures 5. The cycle time ratio was normalized with the results of pattern A set as 100. For Operator B's pattern b, data could not be obtained due to strong discomfort when wearing the HMD. Similarly, for Operator D's pattern b, only one run could be conducted due to the same reason, so only one data point is presented. T-test was conducted using the data of five cycle times to determine if the difference in cycle time ratio due to the difference in experimental patterns was significant. A significance probability p less than 0.05 was considered significant, and a star mark ★ was added to the graph. However, for Operator D's pattern a and b, and between b and c, as mentioned above, since there was only one data point for pattern b, a t-test was not conducted, and a star mark was added to the graph. According to Figures 5, the average cycle time ratio under experimental pattern e is 220.6, and the construction productivity compared to experimental pattern a (manned operation) is about 45%. This is consistent with the results of previous studies. Furthermore, the differences in cycle time ratios between experimental patterns are shown in Table 6. Positive values indicate an increase in cycle time, i.e., a reduction in construction productivity, while negative values indicate an improvement in construction productivity. Similar to the graphs, environments with significant differences are marked with a star ★.

5 Discussion

Based on Table 6, we examined how the differences in each operation environment affected the reduction in construction productivity in this experiment.

- **Difference in Visual Information (Experimental pattern a→b)**
  According to Table 6, among the three operators for whom data was available, two showed a significant difference in cycle time ratio due to the difference in visual information, with an increase in the value (approximately 33-43%). For the remaining operator, the difference in cycle time ratio also showed a significant increase (approximately 94%). This suggests that the difference in visual information is a major factor in reduced construction productivity.
- **Difference in Sensory Information (Experimental pattern b→c)**
  According to Table 6, among the three operators for whom data was available, two did not show a significant difference in cycle time ratio due to the difference in sensory information. For the remaining operator, the cycle time ratio decreased, indicating an improvement in construction productivity, and the difference was very small (approximately 2%). This suggests that the difference in sensory information is not a major factor in reduced construction productivity.
- **Difference in Image Display (Experimental pattern c→d)**
  According to Table 6, none of the operators showed a significant difference in cycle time ratio due to the difference in image display. This suggests that the difference in image display is not a major factor in reduced construction productivity.
- **Difference in Operation I/F (Experimental pattern d→e)**
  According to Table 6, among the four operators, one did not show a significant difference in cycle time ratio due to the difference in operation I/F. However, for all other operators, there was a significant difference in cycle time ratio due to the difference in operation I/F, with an increase in the value (approximately 25-105%). This suggests that the difference in operation I/F can be a major factor in reduced construction productivity for some operators.

From these results, it can be said that the major factors in the decrease of construction productivity in unmanned construction are differences in visual information and operation I/F.

6 Conclusion

To examine the factors leading to a decrease in construction productivity in unmanned construction, remote operation experiments were conducted using the model task. From these experimental results, the following points were clarified:

1) The major factors in the decrease of construction productivity during unmanned construction are "differences in visual information for situational awareness" and "differences in operating interface".

2) "Differences in sensory information" and "differences in image display" are not major factors in the decrease of construction productivity.

The above results 1) and 2) are specific to tasks like the model task involving excavation work with hydraulic excavators, and for other tasks such as off-road driving or breaking work with breakers, sensory information like machine tilt, sound, and vibration may become important. Further examination under various construction patterns is desired in the future. Furthermore, we have incorporated 'cycle time' as a criterion for evaluation within the framework of our proposed model in Task II, undertaking an analysis of the elements that diminish construction efficiency. However, 'cycle time' permits only the appraisal of the entire task, with assessments of more granular details within the task being constrained. For precise evaluations, future research should explore methodologies that consider the operator's visual perspective, movements of the control lever, and hydraulic dynamics.

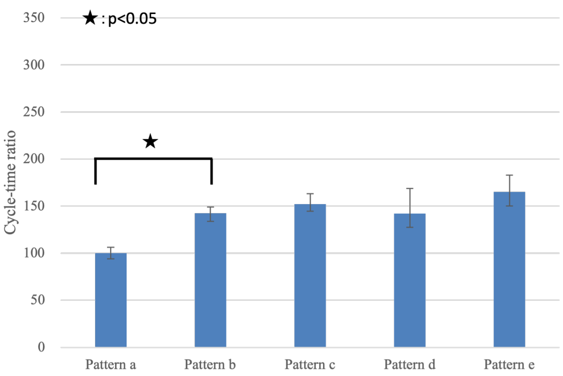
Unmanned construction is expected to be a technology that contributes not only to disaster response but also to improving productivity in regular construction sites through work style reform for operators and increased productivity through day and night work. Therefore, improving construction productivity is essential, and further research is desired.

Table 5. Cycle-time ratio comparison between each pattern [s]

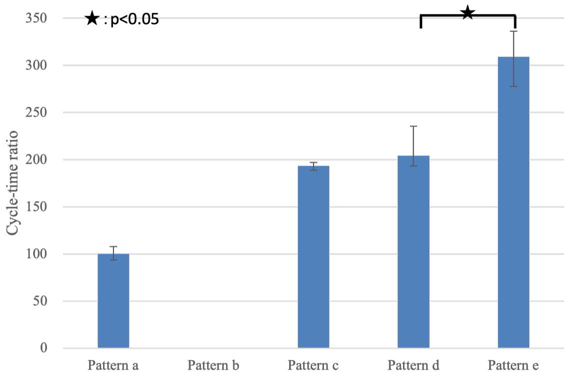
Operator	Pattern a	Pattern b	Pattern c	Pattern d	Pattern e
A	166	237	253	236	274
B	161	-	310	328	497
C	203	270	267	279	331
D	184	358	355	336	453

Table 6. Cycle-time ratio comparison between each pattern

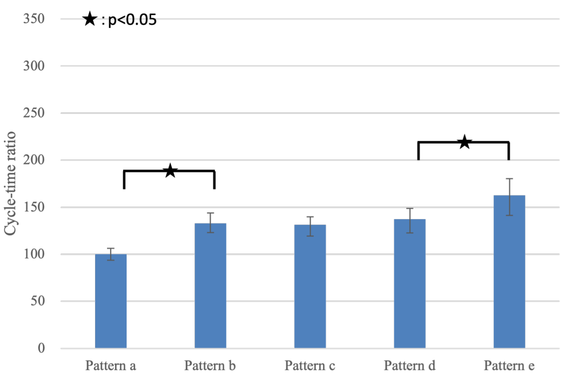
Comparison Factor	Pattern a→b Vision difference	Pattern b→c Body sensation difference	Pattern c→d Visual device difference	Pattern d→e I/F difference
Operator A	42.6★	9.7	-10.1	23.1
Operator B	-	-	11.2	104.8★
Operator C	32.8★	-1.5	6.2	25.3★
Operator D	94.1	-1.7	-10.3	63.5★



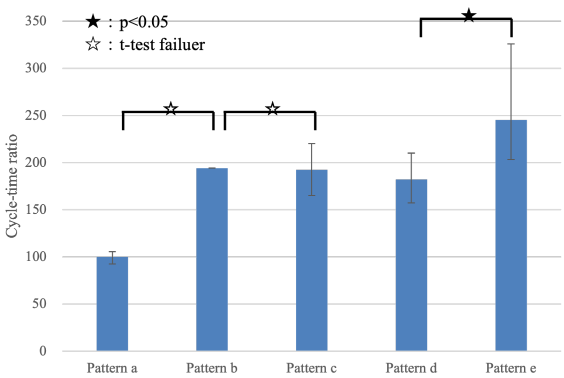
(a) Operator A's result



(b) Operator B's result



(c) Operator C's result



(d) Operator D's result

Figure 5. Experimental results of cycle-time ratios by each operator

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