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Measuring productivity improvement by Machine Guidance through work sampling in earthwork

Julee Eom[1*], Youngcheol Kang[2], Yongsei Lee[3], Pyungho Choi[4]

[1] *Graduate Research Assistant, Department of Architecture & Architectural Engineering, Yonsei University, South Korea*, E-mail address: jleom@yonsei.ac.kr

[2] *Assistant Professor, Department of Architecture & Architectural Engineering, Yonsei University, South Korea*, E-mail address: yckang@yonsei.ac.kr

[3] *Principal Research Engineer, Daewoo Institute of Construction Technology, South Korea*, E-mail address: yongsei.lee@daewooenc.com

[4] *Executive Director, YoungShine D&C, South Korea,* E-mail address: cceagle@youngshine.net

Abstract

This paper proposes a study measuring productivity improvement by using a type of technology called "Machine Guidance" through work sampling in earthwork. Earthwork is the activity typically on the critical path, indicating that productivity for the activity is critical for managing schedule on time. Thanks to the development of sensing and information system technologies, productivity for earthwork has been improved. While there have been many studies investigating the application of a certain type of technology to earthwork, few studies have measured the productivity improvement and presented how the technology leads to productivity improvement. Based on the thorough literature review, it is hypothesized that Machine Guidance contributes to improving productivity of earthwork by reducing indirect workhours spent for information waiting and inspection. In addition to the literature review, this paper presents a research model to test the hypothesis by using the work sampling technique. By proving and quantifying the productivity improvement from the technology use, this study can help practitioners justify the investment for technology use, which will contribute to the deployment of technology and more effective execution of earthwork.

Key words: Machine guidance, Productivity, Work sampling, Measurement method

1. INTRODUCTION

Earthwork is the process of moving large amounts of materials such as soils and rocks through excavation, transportation, and filling. As a basic activity of all civil and building construction projects, earthwork is typically on the critical path that has a great impact on managing construction projects. As activities in earthwork are typically equipment-driven, performance of earthwork highly depends on how equipment for the activities is utilized [1]. With the development of technologies such as sensors, machinery, and information technologies, performance of earthwork has been improved in terms of productivity, safety, and equipment operation and maintenance [2].

Various types of technologies have been applied to earthwork. For example, Chi and Caldas (2012) investigated the 3D object tracking and identification technologies to monitor any safety violations for earthmoving activities which are conducted in dynamic circumstances [3]. Azar and Kamat (2017) discussed that remote control and autonomous operation of earthmoving equipment are important areas for the future research studies [2].

This study investigates a type of technology called Machine Guidance (MG). The technology uses multiple sensors and information systems to enhance the utilization and operation of excavators by providing visual guides to operator. For the slope excavation, an operator of excavation equipment needs a surveyor who checks the level and makes sure that the slope is cut as designed. In addition, the slope excavation should be inspected by construction supervision whether the work is performed to the planned level during excavation [4]. If the supervisor does not check the work right away, the operator should wait, which is time-consuming without adding any value. MG provides information about the slope in terms of vertical and horizontal visuals to the operator. Thus, for the operator of equipment with MG, there is no surveying required. In addition, the operator can move to the neighborhood area for additional work without inspection by the supervisor.

Several studies investigated MG and showed the productivity improvement in terms of quantity. For example, Azar et al. (2015) showed 19% to 23% productivity improvement for excavators from two case studies [5]. The study also presented that MG contributed to reducing the need for surveying work hours by 30% to 5%. Another research found that equipment with MG worked 38.3% of additional volume for 4 working days although the increase per a day varied depending on the driver's competence to MG and the complexity of the excavation terrain [4].

While there have been a number of studies demonstrating the productivity improvement by MG, most of the studies showed the productivity improvement by increased quantity. Studies showing that quantity per unit time has increased by MG can validate that MG contributes to productivity improvement. However, they cannot show how such productivity improvement has been achieved. In order to address the issue, it is necessary to measure the productivity improvement by work sampling. Work sampling measures time for an operator to perform activities and classified time into three types: direct, support (indirect), and delay (idle). As MG provides information that operators need, their indirect work hours which are spent for operations other than excavation such as surveying, stakeout, and grade check can be reduced. The reduced indirect work hours can lead to more direct work hours, time directly spent for excavation work. As more direct work hours indicate that excavators can spend more time for excavation work, quantity per unit time should increase. Indeed, classifying on-site labor’s work hours into categories such as direct, indirect and idle helps to measure the time expenditures of workers easily, and identify the productivity inhibitors that must be reduced to let workers have more time for direct work [6].

This study investigates the productivity improvement by MG on excavators by work sampling. The time excavators spent is classified into three categories: direct, indirect, and idle. The basic hypothesis is that MG contributes to lowering indirect work hours and increasing direct work hours, which will eventually lead to increased productivity. In this paper, literature review about MG as well as productivity and its measurement methods are provided. In the Research Methodology section, work sampling and methods to measure time for the work sampling are presented. Section 4 presents the Expected Finding. This is followed by Future Study and Contribution in Section 5.

2. LITERATURE REVIEW

2.1. Machine Guidance

Machine guidance (MG) is relatively new in the heavy machinery-oriented earthwork engineering. MG utilizes multiple sensing and information system technologies to provide location information in real time, enabling equipment operators to work quickly with high accuracy [2].

The basic operating principle of MG is that the location-based guidance system, which is global positioning system (GPS) based, is displayed on the display board mounted on the excavator through the Digital Terrain Model with 3D design drawings with location and direction information. Through the slope sensor, the distance from the body of equipment to the end of the bucket can be determined with a trigonometric function. In addition, body inclination measurement sensor gives the information about whether the excavator is inclined (Fig.1). If an excavator cut soil for slope, the technology provides location information such as an angle of the slope. With the information, the operator can make sure whether or not he worked to the planned level [4]. As the technology provides such information accurately, there is no need to have a surveyor who checked the angle. In addition, the operator can move to the neighborhood area for additional work without the work check by the supervisor. By saving such time with high accuracy, it contributes to not only improving efficiency and productivity, but also saving man-hours being spent for inspection. Another benefit of using MG is the precise and detailed 3D modeling of the earthwork section. Based on this, it is possible to carry out excavation work at a small cost and time, as well as to accurately predict the amount of earthwork [7]. Based on survey responses from various MG users, Vennapusa et al. (2015) reported 10 to 70% cost reduction resulting from productivity improvement according to the prediction of earthwork volume [8].

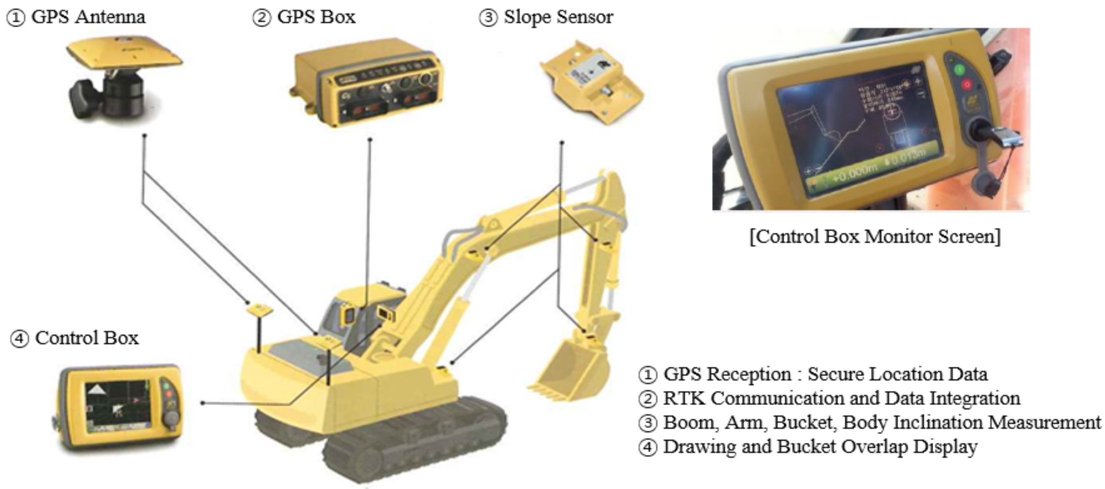

Figure 1. Machine Guidance

2.2. Construction Industry Productivity and Measurement Methods

Productivity is the ratio of input and output [9]. As there are various types of input such as cost and time in terms of labor work hours and output such as value and quantity, productivity has been defined in several ways in the construction industry. For example, the aggregate level productivity which considers the annual value created in the construction industry measured in terms of constant dollar of contracts and overall workhous of hourly workers represents the productivity in the industry level [10]. The activity-level productivity, on the other hand, focuses on the input required for an activity (i.e., workhours spent for an activity) and the output from the activity (i.e., installed quantity) [11]. One advantage of using the activity-level productivity measure is that comparisons of input and output are relatively easy as the productivity for the construction work itself is not affected by construction economic fluctuation [12]. In addition, productivity measures can be classified depending on how various input and output dimensions such as labor workhour, material quantity, and capital are taken into account. While total factor productivity combines all dimensions into one value, single factor productivity calculates the productivity by dimension separately [13]. However, these metrics have been criticized as they are often calculated after the work has been completed. If productivity is measured by these metrics, activities with low productivity are identified long after the activity is firstly implemented on site [6].

In response to this concern, work sampling can be applied to identify problems in a timelier manner as measurement of direct work hour is broadly accepted by managers for an early indicator of productivity issues [6]. Work Sampling refers to measuring the time it takes for an operator to perform activities classified into three types: direct, support, and delay [11]. Direct work hour refers to the time spent in productive work. Support work hours are time spent for management, supervision, planning, guidance, travel time and tool movement. Delay refers to the time spent waiting for the post-process to finish, personal time and late start and early finish of work. Indeed, these terms are commonly used in other studies using the work sampling techniques with slightly different names. Chang and Yoo (2013) had two categories: effective work hour which is similar to direct work hour and ineffective work hour covering both support work hour and idle time [14]. Hwang et al. (2014) classified those as productive work hour, unproductive work hour, and idle time [15].

With these categories, various researchers analyzed how construction labors' work hours were spent in the field. Jergeas et al. (2000) found that 33%, 35%, and 32% of labors' work hours were categorized as direct work hour, indirect work hour, and idle time, respectively [13]. By measuring the work hours for masonry workers, Chang and Yoo found that 39.4% of their time was direct work hour, indicating that 23.64 minutes per hour was used productively [14]. By considering the fact that the percentage of direct work hours is consistently low from various studies, one can argue that there is a lot of room to improve productivity by increasing the direct work hour. Technologies such as MG can contribute to such improvement.

When conducting the work sampling technique to measure how work hours are spent in the field, one issue is how to measure the hours accurately. For the studies investigating construction equipment, various methodologies (e.g., image-processing, computer-vision based video interpretation model, machine learning and accelerometers etc.) have been used to measure the operation time of construction equipment. For example, hydraulic excavator's equipment idle time is estimated by using Hues, Saturations, and Values (HSV) color space [16]. Automated video interpretation model was employed to a concrete column pour operation by defining each status as waiting, idle and working [17]. Akhavian and Behzadan (2015) conducted a case study for front-end loader's activity such as engine off, idle, moving, scooping, and dumping to precisely extract activity durations by using mobile sensor and machine learning classifiers [18]. Computer vision-based algorithm for recognizing single actions such as moving, digging, hauling, swinging, and dumping of earthmoving construction equipment was presented using an algorithm which automatically learns the distributions of the spatio-temporal features and action categories [19]. As accelerometers provide a low-cost and nonintrusive monitoring system of the equipment operation, they are mounted on excavator to calculate the operational efficiency [20]. Abbasian-Hosseini et al. (2016) focused on the idle time of construction equipment as it can have the negative impact environmentally [21]. Akhavian and Behzadan (2015) used a distributed sensor network to collect data from dump truck to reduce the idle time and used discrete-event simulation to model earthmoving operation for producing measurable emission rate at the non-idle/idle rate [18]. Estimated engine speed has been used to estimated emission rates of each diesel vehicles in earthmoving activities such as idling, scooping, and dumping [22]. In summary, there are various types of technologies available to measure the work hours of construction equipment for the work sampling technique.

3. RESEARCH METHODOLOGY

3.1. Work sampling

For the work sampling in this study, we used three terms: direct work hour, indirect work hour, and idle time. As we applied the work sampling for excavation, we defined each term as shown in Table 1. Direct work hour is productive time spent for excavation work itself. Indirect work hour is time taken to support excavation activity. It includes surveying during or after excavation, grade checking to see whether the slope is excavated as planned. Lastly, idle time is time used regardless to excavation. This includes personal time of workers and late start or early finish.

Table 1. Definition of time factor

No.	Time Factor	Definition	Activities
1	Direct work hour	Productive time spent on work	Excavation
2	Indirect work hour	Time taken to perform related work	Surveying, Grade checking
3	Idle time	Time taken without regard to work	Personal time, Late start/Early finish

3.2. Measurement Method

We will compare the direct, indirect work hours for the excavators with and without MG. For the comparison, it is important to measure each time accurately. Thus, it is necessary to find a proper measurement method for time.

Videotaping is one good candidate for the time measure to conduct the work sampling. Even though it is effective and inexpensive, it takes intensive manual reviewing process and time for analysis [17]. Many other technologies have been investigated for automatic and accurate measurement of construction equipment's operation time. To find the most suitable method for work sampling technique, we will first look at several methodologies. Those methodologies can be classified into three categories as shown in Table 2.

The automatic analysis of recorded images or video uses cameras and image-processing techniques. As it is common to use cameras which produce images every 5 to 30 seconds at construction sites to monitor the construction activities nowadays, those abundant image data provide an opportunity to use an image processing approach to automatically measure idle time of construction equipment. There are several technical issues for estimating the equipment's idle time with this technology. These include the distinction between equipment and its background and determination on the equipment's status through the images. One possible solution is equipment segmentation by threshold setting approach in the HSV color space. Equipment can be tracked by using the concept of distances between objects as the location of equipment would be close in a series of images. Equipment is considered to have moved when the distance between the location of an equipment's centroid differs by more than the threshold value. The approach is known to be quite accurate. The error rate for this image processing-based method was 4.1% [16]. Another video interpretation model is investigated by Gong and Caldas (2010) [17]. This video interpretation model involves three video processing hierarchy stages. First stage uses computer vision techniques to recognize what construction objects are in the video. Second stage uses model-based computer reasoning to interpret what happens in the video. Last stage deals with using video content organization method to summarize what happened in the video. For the validation of the proposed video interpretation model, model was applied to a concrete column pour operation. Results showed average 98.85% of accuracy rate.

Besides these automatic analyses of recorded images or video, sensors can be mounted on construction equipment to diagnose its status. An accelerometer is an electromechanical device that measures acceleration. Based on acceleration data captured by small-sized, low-cost microelectromechanical (MEMS) accelerometers that are installed on equipment, operation time of construction equipment can be analyzed. Ahn et al. (2015) used the sensor to diagnose the status of construction equipment [20]. The underlying idea is that any nonstationary operating of construction equipment generates a notable level of acceleration compared to base line and any stationary operating of equipment creates distinguishable patterns of acceleration signals. By using this idea, they achieved over 93% of the accuracy with less than 2% deviation between the observed and measured in most cases [20]. Mobile sensors also can be used in the work sampling for construction equipment. Akhavian and Behzadan (2015) collected multi-modal data from various sensors (i.e. accelerometer, gyroscope, GPS, RFID) embedded in mobile devices placed inside construction equipment cabins [18]. Although the accuracy depended on the level of detail in classifying equipment's actions, the overall accuracy exceeds 80%.

Information from construction equipment itself is another source being used to diagnose the status of construction equipment for work sampling. Examples of such information include emission from equipment and engine speed. As many local jurisdictions limit the amount of time diesel engine equipment run at idle without shutting down, construction equipment's idle time is one of the issues in the fields of environmental pollution [21]. As emission factors associated with idling is significantly different from other activities, engine speed or fuel consumption is estimated based on emission factors like concentrations of carbon dioxide (CO_2), nitrogen oxides (NO_X), hydrocarbons (HC), and carbon monoxide (CO) [22].

Table 2. Measurement method

No.	Type	Methodology	Author, year
1	Automatic analysis of recorded images or video	Image-processing Computer vision-based video interpretation	Zou and kim (2005) [16] Gong and Caldas (2010) [17]
2	Sensor	MEMS accelerometer Mobile sensors (i.e. accelerometer, gyroscope, GPS, RFID)	Ahn et al. (2015) [20] Akhavian and Behzadan (2015) [18]
3	Using information from construction equipment itself	Engine speed or fuel consumption estimated by emission concentrations	Heidari and Marr (2015) [22]

As each methodology has different characteristics, it is important to find the most suitable method for work sampling considering several factors. After selecting an appropriate method, we will compare the productivity in terms of time for excavators with and without MG when excavating same amount of soil. It is hypothesized that excavators with MG should have higher level of direct work hours. The rationale behind this hypothesis is that as MG provides information that operators want in real time, they do not need to wait for surveying or confirmation from inspectors. Thus, they can spend more time directly for excavating. By comparing the productivity improvement with or without the use of machine guidance through work sampling, we will show the improvement of productivity due to the increase in the direct work hours and decrease in the indirect work hours.

4. EXPECTED FINDING

By using the work sampling technique with selected measurement methods, utilization of operation time of excavator with and without MG will be investigated. For the measurement method selection, to pursue accuracy of measuring direct work hour, indirect work hour, and idle time, we considered to employ multiple methods among the methods in Table 2. Based on the previous studies using the work sampling technique, it is reasonable to assume that the direct work hours for the excavators without MG take at most 40% of total work hours. This indicates that more than 50% of work hours will be used for nonproductive works. Even if excluding the idle time caused by personal time or early finish and late start due to uncertainties at worksite due to weather and interference process, much of those nonproductive usage of time stems from time spent for extra surveying before and after excavation or grade checking by a surveyor. Due to these indirect activities, excavator operators should keep stopping and re-starting their works, which should hinder their productivity.

Using MG, on the other hand, should help the operators obtain every information needed during excavation in real time. In other words, MG helps to reduce indirect work hours spent for information delivery and inspection of the work. With the technology, significant portion of indirect work hours can be transferred to direct work hours, which should contribute to productivity improvement.

5. CONCLUSION

Earthwork is one important process typically being on a critical path in schedule management. However, earthwork has been carried out through traditional procedures such as surveying and stakeout. For past few decades, technology using sensing and information systems has been applied to earthwork equipment. MG is one of those technologies which provides real-time location information enabling the equipment operators to work quickly with high accuracy. MG enables to excavate without surveying before and after excavation as the technology provides topographic information to operators. It is also helpful in checking the level without surveyors throughout the operation.

As this study focuses on measuring productivity in terms of work hours on-site, work sampling is suggested for investigating of time utilization of excavator. To employ the method, it is necessary to diagnose the status of equipment and measure the time in terms of direct work hours, indirect work hours, and idle time. This study reviewed three different measurement methods using various technologies in Table 2. For the direction of future research, it is necessary to select measurement methods that best fit to our work sampling circumstances. For the selection, there should be some factors taken into account. For accuracy, it is important to establish rigid criteria for automatically matching the direct work hour, indirect work hour, and idle time. Distinguishing between indirect work hour and idle time can be a challenge for automatic measurement, as the excavator's motions related to indirect work hours and idle time should be very similar. Indeed, it is necessary to further discuss how to distinguish both in the context of the work.

Regarding the contribution of this study, while many previous studies about productivity improvement from the use of technology on construction equipment have focused on the increase of installed quantity, this study focuses on the direct work hours based on the work sampling technique. With this, this study should be able to explain why and how the productivity improvement was achieved. There have been few studies investigating why technologies contribute to productivity improvement. If this study verifies the hypothesis that equipment with MG spends has higher level of direct work hours and lower level of indirect work hours, it will help practitioners when they justify their decisions to invest in technology and design their work processes to gain higher level of productivity improvement.

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