Excavation Path Generation for Autonomous Excavator Considering Bulking Factor of Soil

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Abstract -

This paper proposes an excavation path generation method for autonomous excavators by considering the bulking factor of soil. In existing research on autonomous excavation, the excavator's path was manually planned, based on known soil properties. Thus, the efficiency of the excavation process may reduce in situations where the soil properties are unknown. To address this problem, this paper proposes a novel method for generating an excavation path based on the bulking factor and for realizing an efficient excavation for any soil type. The bulking factor is estimated by sensing data of the target soil during the excavation. The experimental results show that the proposed method can generate an efficient excavation path for different soil properties.

Keywords -

Excavation; Path Planning; Bulking Factor of Soil

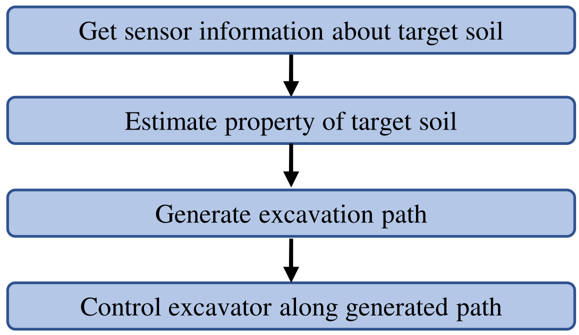


Figure 1. Overall process of autonomous excavation

1 Introduction

The demand for high efficiency in construction sites has increased recently, to cover the shortage of labor force caused by the aging society. An excavator is one of the most frequently used machines in construction sites. Its manipulation requires sophisticated skills, and the efficiency of the excavation process highly depends on each operator's skill. The main labor force of this task comprises experienced and aged operators, but the number of such skillful experts is sure to decrease in the future. To address this problem, excavators should be able to perform the excavation process by themselves, instead of being manipulated by an operator.

Yoo et al. proposed a dynamic optimal trajectory generation method for controlling an autonomous excavator[1]. In this method, trajectory generation is formularized as a motion optimization problem under a finite-dimensional set of linear constraints. By solving this optimization problem, an excavation trajectory that minimizes the energy consumption can be obtained. However, this method does not consider the interaction between the excavator tools and the soil. Therefore, it is unclear whether this method will even work in an actual excavation process.

Yamamoto et al. developed a prototype of an autonomous hydraulic excavator using 3-D information of the construction model and successfully demonstrated the autonomous operation of hydraulic excavators[2]. However, while this method does not require any orders from human operators during the excavation process, the users must manually specify the excavation path in advance according to the target soil's properties. Therefore, the efficiency of the excavation process might degrade in a situation where the soil properties are unknown.

To address the above-mentioned problems, this study aims to establish an excavation path generation method that guarantees high efficiency based on the soil type. For this purpose, the excavator must automatically generate an excavation path itself according to the property of the target soil. Therefore, we focus on the bulking factor of soil, which is a soil property frequently used in construction sites, as an indicator of soil type. By considering the bulking factor of the target soil, we realize an efficient excavation for different soil types.

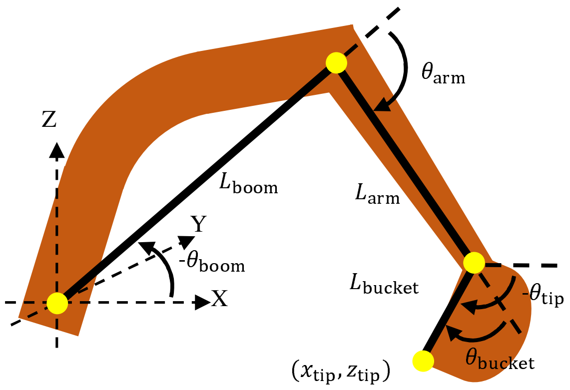


Figure 2. Parameters for hydraulic excavator

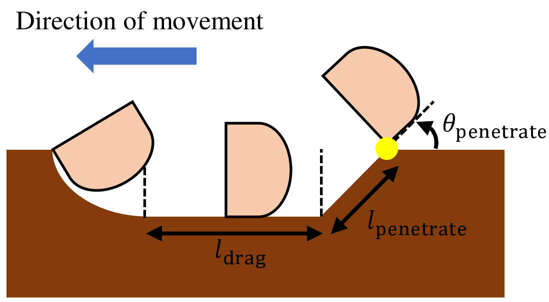


Figure 3. Modeled excavation path

The remainder of this paper is organized as follows. In Section 2, the proposed excavation path generation method is explained in detail. Then, the validity of the proposed method is reported in Sections 3 and 4, which include a simulation experiment and a field experiment, respectively. Finally, Section 5 provides the conclusions for this study.

2 Proposed Method

2.1 Overall Process of Autonomous Excavation

The overall process of the proposed autonomous excavation is summarized in Fig. 1. First, the system measures the changes in the soil bulk before and after excavation. For this purpose, an RGB-D sensor is utilized in this study. Then, the bulking factor is estimated using the sensing data before and after excavation. Further, an excavation path is generated according to the bulking factor of the target soil. Finally, the excavator is controlled to follow the generated path. This study assumes that the excavator can be controlled along the generated path using previous methods, such as [3] or [4]. Thus, this study aims to develop an excavation path generation method.

2.2 Problem Settings

The target machine of this study is a hydraulic excavator, whose parameters are depicted in Fig. 2. The operating parts of the hydraulic excavator include a boom, an arm, and a bucket, in this order, starting from the main body. The rotation joint in each part can be controlled by the hydraulic actuator mounted on each part. Here, it is assumed that the excavator will not rotate along the Z-axis; thus, the generation of the excavation path on the XZ plane can be discussed. In addition, it is assumed that the position of the excavator itself will not change. Under these assumptions, we find a set of appropriate parameters $[\theta_{boom}, \theta_{arm}, \theta_{bucket}]$ for the entire excavation process.

2.3 Excavation Model

In this study, the excavation process is modeled using three parameters: $[\theta_{penetrate}, l_{penetrate}, and l_{drag}]$. In this modeling, we refer to the excavation motion performed by experienced operators as a reference. In general, the excavation motion can be classified into three phases: penetrate, drag, and scoop [5]. In the penetration phase, the operators pierce the surface of the target soil using the bucket edge and move the bucket until it reaches the bottom line. Then, the bucket is dragged horizontally along the bottom line. Finally, to collect the accumulated soil into the bucket, the scooping motion is executed. To model this excavation motion, the three above-mentioned parameters have been used; the excavation path represented by them is illustrated in Fig. 3. Here, $\theta_{penetrate}$ indicates the angle between the soil surface and the penetrating line, $l_{penetrate}$ indicates the length of the penetrating line, and l_{drag} indicates the length of the dragging line. In the scooping phase, only the bucket part is rotated by 90°, with the tip of the arm part fixed in position. Once these parameters are determined, the position of the bucket tip and the rotation of the bucket over the whole excavation process can be determined. By using this position and rotation of the bucket, the parameters $[\theta_{boom}, \theta_{arm}, and \theta_{bucket}]$, explained in section 2.2, can be calculated using inverse kinematics.

2.4 Bulking Factor of Soil

As discussed in Section 2.3, three parameters have been used to specify the excavation model. The values of these parameters need to be defined. In this respect, the soil property is accounted for so that the generated path can guarantee its efficiency for different soil types. For this purpose, this study considers the bulking factor of soil, which is a soil property based on the phenomenon observed in the excavation process [6]. In general, the exca-

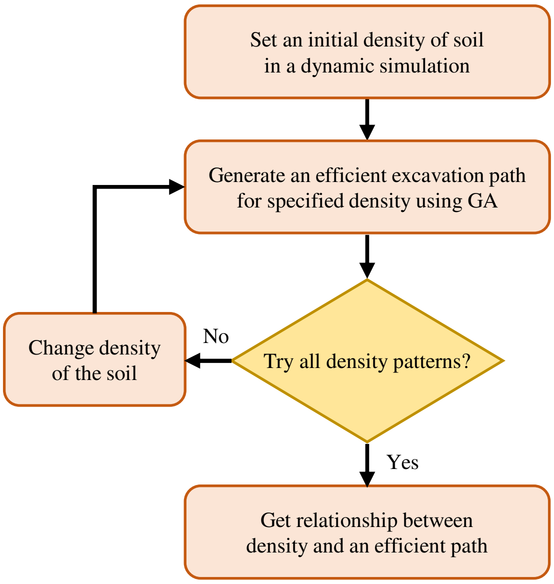


Figure 4. Excavation path generation process

vated soil particles do not fit together as they did before excavation, which increases the void space among these particles. Thus, the soil volume increases after excavation, and the bulking factor of soil is used to quantify this volume increase. Qualitatively, soil with a large bulking factor means the soil is hard. Conversely, soil with a small bulking factor means the soil is soft. Assuming k to be a bulking factor of soil, it can be defined as follows:

$$k = \frac{V_{\text{after}}}{V_{\text{before}}}, \quad (1)$$

where V_{after} and V_{before} denote the volumes after and before excavation, respectively. In related works, there are other properties of soil such as soil density used in [7]. However, this study focuses on the bulking factor of soil because of its simplicity of measurement. Compared to the other properties of soil, the bulking factor can be easily calculated, by simply measuring the volumes before and after excavation with an RGB-D sensor.

2.5 Path Generation with Dynamic Simulator

In this section, the excavation path generation method using a dynamic simulator has been explained. As discussed in Section 2.4, the proposed method generates an efficient excavation path based on the soil properties, to guarantee efficient excavation for any soil type. To enable this, the proposed method learns the relation between the soil property and an efficient excavation path using a dynamic simulator before executing the actual excavation. The use of a dynamic simulator allows us to replicate the interaction between the excavator and soil during the excavation process. In addition, the properties of the target soil can be changed by specifying the simulator parameters.

The process of excavation path generation using a dynamic simulator is shown in Fig. 4. To understand the relation between soil property and an efficient excavation path, efficient excavation paths for different soil properties were determined in advance. Specifically, an efficient excavation path is generated while changing the initial density of soil in the simulation. In terms of the method for finding an efficient excavation path for each condition, a genetic algorithm (GA) is used, where the excavation model parameters $[\theta_{\text{penetrate}}, l_{\text{penetrate}}, and l_{\text{drag}}]$ are regarded as the genes of each individual. Based on this setting, the fitness of each individual is defined as follows:

$$f = \frac{V_d}{E}, \quad (2)$$

where f denotes the fitness of each individual, V_d denotes the volume of soil accumulated in the bucket during one excavation motion, and E denotes the total energy consumed by the excavator joints during the excavation motion. According to this formalization, an efficient excavation path is ideally assigned high fitness. Thus, an efficient excavation path can be obtained as the final output of GA. This operation is repeated until an efficient excavation path for all density patterns is obtained. Furthermore, the relation between the density and efficient excavation path is obtained, which will be used for path selection during the actual excavation process.

2.6 Path Selection via Bulking Factor

In this section, the path selection method based on the bulking factor has been explained. As discussed in Section 2.5, the proposed method has already analyzed the relation between the soil density and an efficient excavation path through a dynamic simulator. These findings are used in the process of path selection. However, it is not easy to measure the density of the target soil directly. Therefore, the bulking factor of soil is used to estimate the soil density because measuring the bulking factor is not difficult. In terms of the density estimation method, empirical knowledge is used. According to the model described in [8], higher the soil density, larger is the bulking factor. In this way, the soil density is estimated via the bulking factor calculated using the measurement data. After we obtain information about the density of the target soil, we select an efficient excavation path using the knowledge gained via the dynamic simulator.

Table 1. Conditions of the genetic algorithm

Parameters	Value
Number of generations	10
Number of individuals	15
Probability of crossover	0.8
Probability of mutation	0.05

Table 2. Lower and upper limits

Parameters	Lower limit	Upper limit
$\theta_{penetrate}$	$\pi/6$	$\pi/3$
$l_{penetrate}$	0.1 [m]	0.6 [m]
l_{drag}	0.1 [m]	0.6 [m]

3 Simulation Experiment

3.1 Experimental Setting

To verify the effectiveness of the proposed excavation path generation method, a simulation experiment was conducted, where Vortex Studio by CM Labs Simulation was used as the dynamic simulator. The Vortex Studio can evaluate the interaction between the excavator and soil during the excavation process based on the soil mechanics. Furthermore, the density of the target soil can be changed by specifying the simulator parameters. First, the proposed method learns the relation between the soil density and an efficient excavation path in the simulation environment based on a GA, whose conditions are listed in Table 1. Each individual has three parameters, $[\theta_{penetrate}, l_{penetrate}, and l_{drag}]$, as genes. Initially, each gene is randomly determined within the specified range. The lower and upper limits of each gene have been listed in Table 2. Under these conditions, the GA finds an efficient excavation path for all density settings. In this experiment, the density settings were set from 0% to 100%, in continuous increments of 10%.

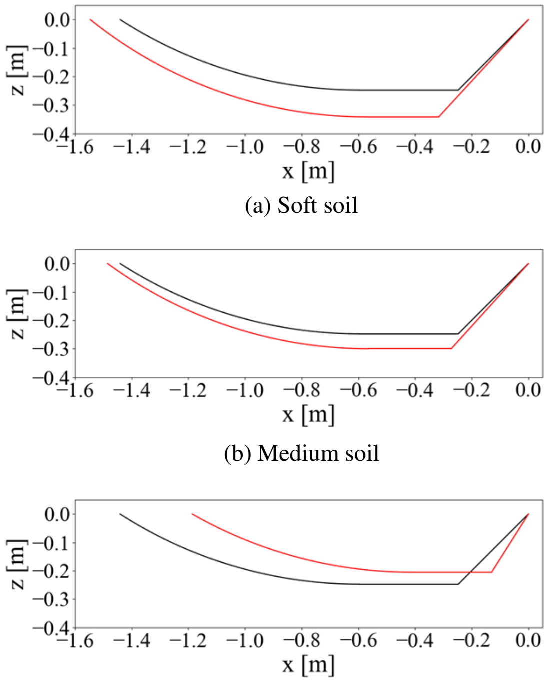
After this learning process, the actual excavation motion was performed using the proposed method as follows:

- Excavating the target soil once with fixed parameters and calculating its bulking factor.
- Estimating the target soil ' s density, based on its bulking factor.
- Selecting an efficient excavation path according to the estimated density.
- Controlling the excavator along the selected excavation path and measuring its efficiency.

The above procedure was performed under several conditions to determine the excavation efficiency generated by the proposed method. These conditions have been discussed in Table 3. For comparison, the excavation efficiency was measured in the case where the proposed method was not used. In this case, the motion parameters

Table 3. Three conditions of soil

Conditions	Density [%]
Soft soil	20
Medium soil	50
Hard soil	80



(a) Soft soil

(b) Medium soil

(c) Hard soil

Figure 5. Calculation results for each condition

$[\theta_{penetrate}, l_{penetrate}, and l_{drag}]$ were set to $[\pi/6, 0.35, 0.35]$, respectively.

3.2 Experimental Result

Figure 5 shows the calculation results for each condition. In Fig. 5, (a) shows the result for soft soil, (b) shows the result for medium soil and (c) shows the result for hard soil. In each graph, the red line shows the trajectory of bucket tip in case of using the proposed method, while the black line shows the trajectory of bucket tip in case of not using the proposed method. Here, the origin [x, z] = [0, 0] is defined as a position where an excavator starts penetrating. As shown in Fig. 5, the proposed method changed the excavation path according to the soil condition. Figures 6 and 7 show the results of the simulation experiment. Figure 6 shows the efficiency of soft and medium soil and Figure 7 shows the efficiency of hard soil. In each graph, the left light-blue bar shows the excavation efficiency in case of not using the proposed method, while the right dark-blue bar shows the excavation efficiency generated by the proposed method. As shown in Figs. 6 and 7, the

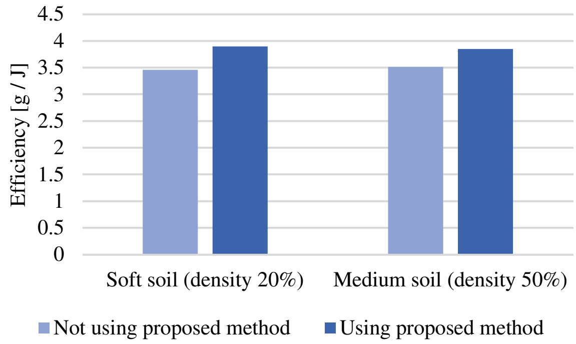


Figure 6. Efficiency of soft and medium soil

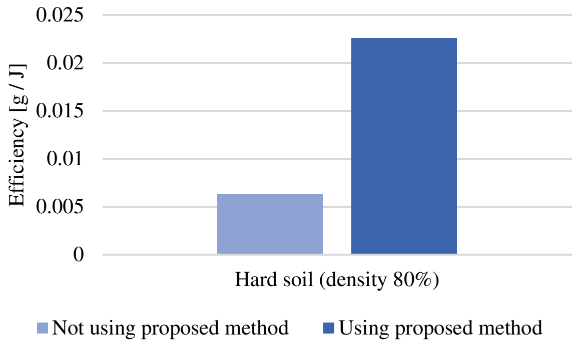


Figure 7. Efficiency of hard soil

proposed method can improve the excavation efficiency. Particularly in the case of hard soil, the proposed method improves the efficiency by more than 200 %. Therefore, it was confirmed that the proposed excavation path generation method can improve the excavation efficiency for any soil type.

4 Field Experiment

4.1 Experimental Setting

To confirm the feasibility of calculating the bulking factor of soil, a field experiment was conducted using an RGB-D sensor. In this experiment, ZAXIS120, developed by Hitachi Construction Machinery, was used as a hydraulic excavator and Intel Real Sense Depth Camera D435i, developed by Intel, was used as an RGB-D sensor. The experimental setting is shown in Fig. 6. In the experiment, the bulking factor of soil was calculated using the 3-D measurement data obtained by the RGB-D sensors. Specifically, the volume change of the soil was calculated in both the excavation and dumping areas. In the excavation area, the volume change of soil was calculated by considering the differences in soil volume before and after the excavation. In the dumping area, the volume change

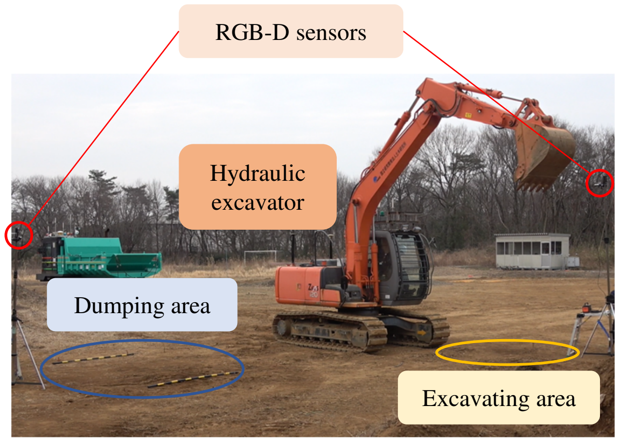
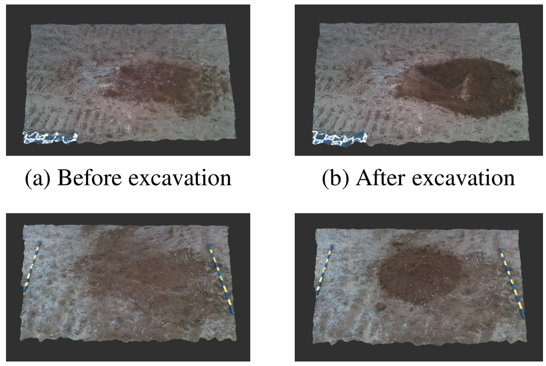


Figure 8. Field experiment setting



(a) Before excavation (b) After excavation

(c) Before dumping (d) After dumping

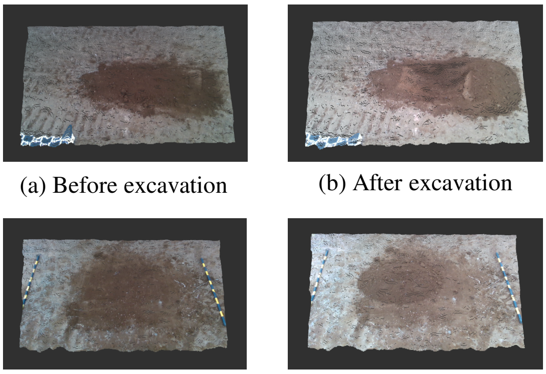
Figure 9. 3-D point cloud data (First trial)

of soil was calculated by considering the differences between the soil volume before and after dumping. Based on the above volume changes, the soil volumes before and after excavation were calculated, and its bulking factor was calculated based on these data.

In this experiment, the bulking factor was calculated under two conditions. For the first trial, compacted soil was excavated. For the second trial, the soil we filled back after the first trial was excavated. Thus, the soil for the second trial was loosened than that in the first trial. This enabled us to confirm the possibility of calculating the bulking factor of soil, which has a different density.

4.2 Experimental Result

The 3-D point cloud data obtained in this experiment are shown in Figs. 9 and 10. Figures 9 and 10 show the data of the first and second trials, respectively. In both these figures, (a) shows the area before excavation, (b) shows the area after excavation, (c) shows the area before dumping, and (d) shows the area after dumping. Table 4 lists the soil



(a) Before excavation (b) After excavation

(c) Before dumping (d) After dumping

Figure 10. 3-D point cloud data (Second trial)

Table 4. Bulking factor k of soil

	$V_{\text{before}}[m^3]$	$V_{\text{after}}[m^3]$	k
First	0.4552	0.6619	1.4540
Second	0.5081	0.5926	1.1663

volume before excavation, V_{before}; that after excavation, V_{after}; and the bulking factor of soil, k, calculated using 3-D point cloud data. As discussed in Table 4, the value of the bulking factor of soil in the first trial is larger than that in the second trial. This indicates the difference in density between the first and second trials. Therefore, the bulking factor of soil can be calculated based on the 3-D measurement data.

5 Conclusion

This paper proposes an excavation path generation method for an autonomous excavator. The proposed method considers the bulking factor of soil as a soil property during the excavation process, which enables the generation of an efficient excavation path for different soil types. A GA was used to determine an efficient excavation path for a specific soil. Additionally, a simulation and a field experiment were conducted to validate the proposed method. For future work, it is necessary to complete the implementation of the entire system on an actual hydraulic excavator and perform full-scale field experiments to validate the proposed method.

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