Development of Sand Volume Estimator for Under-Struck Excavator Bucket Using Single Camera

In-Hwan Kim, Dong-Woo Lim, and Jin-Woo Jung

Department of Computer Science and Engineering, Dongguk University, Seoul, Korea

Ijfis

Abstract

To support the intelligence of construction environment, it is important to measure the workload of excavator in real time. But, previous studies are expensive to implement or can not processed in real time. In this paper, an image-based method to estimate the workload of the excavator bucket especially for the state of under-struck is proposed by assuming the shape of bucket and the shape of sand inside the bucket as geometric models. By analyzing the relation between single camera image and actual bucket geometry, the volume of sand which is proportional to the excavator workload is estimated. The experimental results show 93.5% accuracy even though only some part of sand region is unseen.

Keywords: Sand volume estimator, Excavator bucket modeling, Single camera

1. Introduction

It is not easy to measure in real time the amount of sand which an excavator load in working environment [1, 2]. Previous method to measure this workload in real environment was to measure the charge of weight of dump truck. In order to make this weight change, it is needed to stop the truck in a certain area. However, this method is inefficient in terms of time because it decreases the working efficiency by stopping the truck. This paper proposes a new method which can estimate automatically the volume of sand in a bucket by capturing an image from a single camera in the excavator and analyzing the image specifically focused on the under-struck state.

2. Background

Depending on the amount of sand piled up in a bucket of excavator, states could be divided like Figure 1. It is called as struck state if the volume of bucket and that of sand are equal. It is called as under-struck state if the volume of sand is less than struck state. If the volume of sand is larger than struck state, it is called as heaped state. This paper focuses on under-struck state. The purpose of this paper is to estimate the amount of sand from the bucket image based on a single camera image processing [3, 4].

This paper assumes A1-A4 to estimate the volume of under-struck state.

A1: The shape of bucket is modeled as a combination of half cylinder and right triangular prism.

Received: Dec. 20, 2017
 Revised : Nov. 21, 2018
 Accepted: Dec. 15, 2018

Correspondence to: Jin-Woo Jung
 (jwjung@dongguk.edu)
 ©The Korean Institute of Intelligent Systems

©This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Figure 1. Three representative states of sands in the bucket. (a) under-struck state, (b) struck state, and (c) heaped state.

Figure 2. Bucket image.

A2: The bucket diameter '2a', bucket width 'b' and bucket teeth length 'c' are given by the excavator company.

A3: When the image is captured, the upper side of bucket is horizontal to the ground.

A4: In Figure 2, the pixel locations of points (P_1 to P_8) and the highest vertical line (U) can be calculated with image processing [5, 6].

3. Single Camera-based Sand Volume Estimation Algorithm for Under-Struck State

Under-struck state means that the highest line of sand U is below the line (Figure 3). This state could be divided into three cases in order to reduce the complexity of the formula. (Figure 2) The condition dividing the under-struck state is as follows:

L1: line segment $\overline{AB}$

L2: parallel line segment with $\overline{AB}$ passing through O

L3: Parallel line segment with $\overline{AB}$ passing through D

If ($U < L3$) state $\leftarrow$ Under-Struck-Case1

Else if ($U < L2$) state $\leftarrow$ Under-Struck-Case2

Else if ($U < L1$) state $\leftarrow$ Under-Struck-Case3

Figure 3. Bucket modeling.

Figure 4. Three cases for under-struck state.

Algorithm 3.1. Volume_Estimator

INPUT

$P_1, \dots, P_6$: Six trapezoidal points of the bucket

U : The uppermost edge point of the sand region in photographed image

V_1 : Center point of $\overline{P_1P_2}$

V_2 : Center point of $\overline{P_3P_6}$

V_3 : Center point of $\overline{P_4P_5}$

C : Intersection point of line segment $\overline{V_1V_3}$ and the center line of the image

D_1 : Intersection of $\overline{P_1P_3}$ and $\overline{P_2P_6}$

D_2 : Intersection of $\overline{P_1P_4}$ and $\overline{P_2P_5}$

OUTPUT

V : The volume of sand accumulated in the bucket

FUNCTION

Volume_Estimator($P_1, \dots, P_6, U, V_1, V_2, V_3, C, D_1, D_2$)

1 {

2 $m \leftarrow \frac{V_1C}{V_3C}, m' \leftarrow \frac{V_1C}{UC}, l_w \leftarrow \overline{P_1P_2}, l'_h \leftarrow \overline{V_1U},$
 $l''_h \leftarrow \overline{V_1V_3}, l'''_w \leftarrow \overline{P_7P_5}$

3 $\theta_C \leftarrow \cos^{-1}$

$\left(\frac{f(m+1)\sqrt{4a^2l_w^2\{l_h^2+(m+1)^2f^2\}-b^2l_h^2(m+1)^2f^2-l_h^2(m+1)bf}}{2al_w(l_h^2+f^2(m+1)^2)} \right)$

4 $h \leftarrow \frac{l'_h(m'-1)bf}{l'''_w(m'-1)f \sin \theta_y + lh'l_w'''m' \cos \theta_y}$

```

5  $h \leftarrow \frac{l'_h(m'-1)bf}{l''''_w(m'-1)f \sin \theta_y + lh'l''''_w m' \cos \theta_y}$ 
6 IF ( $h \geq h_0 + a \sin \theta_B$ ) THEN
7   state  $\leftarrow$  Under-Struck-Case1
8 ELSE IF ( $h_0 + a \sin \theta_B > h \geq h_0$ ) THEN
9   state  $\leftarrow$  Under-Struck-Case2
10 ELSE IF ( $h < h_0$ ) THEN //  $h_0 = a \sin \theta_B$ 
11   state  $\leftarrow$  Under-Struck-Case3
12 END IF
13 IF (state=Under-Struck-Case1) THEN
14    $V \leftarrow a^2 b \cos^{-1} \left( \frac{h_l}{a} \right) - bh_l \sqrt{a^2 - h_l^2}$ 
15 ELSE IF (state=Under-Struck-Case2) THEN
16    $V \leftarrow \frac{\pi a^2 b}{2} - \frac{a^2 b}{2} \left( \theta_B + \frac{\pi}{2} - \cos^{-1} \left( \frac{h_l}{a} \right) \right)$ 
17    $- \frac{bh_l}{2} \left( \sqrt{a^2 - h_l^2} + h_l \frac{\cos \theta_B}{\sin \theta_B} \right)$ 
18    $+ \frac{b}{2} \tan \theta_B \left( \frac{a \sin \theta_B - h_l}{\sin \theta_B} \right)^2$ 
19 ELSE IF (state=Under-Struck-Case3) THEN
20    $V \leftarrow \frac{\pi a^2 b}{2} - \frac{b}{2} \tan \theta_B \left( \frac{2a \sin \theta_B - h}{\sin \theta_B} \right)^2$ 
21    $- \frac{a^2 b}{2} \left( \theta_B - \cos^{-1} \left( \frac{\sqrt{a^2 - (a \sin \theta_B - h)^2}}{a} \right) \right)$ 
22    $+ \frac{b}{2} (a \sin \theta_B - h) \left( \sqrt{a^2 - (a \sin \theta_B - h)^2} - \frac{a \sin \theta_B - h}{\tan \theta_B} \right)$ 
23 END IF
24 RETURN V
25 }
```

3.1 Determination of Under-Struck State Parameters

Specific parameters are required to estimate the volume in case of Under-Struck State. There are parameters that need to be known by default such as l_w , l'_w , l''''_w , l'_h , l''''_h , and so on. These basic parameters can be obtained using each point ($P_1 \sim P_8, U$) through image processing.

In Figure 5,

$$l_w = \sqrt{(\alpha_2 - \alpha_1)^2 + (\beta_2 - \beta_1)^2}, \quad (1)$$

$$l''''_w = \sqrt{(\alpha_8 - \alpha_7)^2 + (\beta_8 - \beta_7)^2}, \quad (2)$$

$$l'_h = \sqrt{(\alpha_7 - \alpha_1)^2 + (\beta_7 - \beta_1)^2 - \left(\frac{l_w - l''''_w}{2} \right)^2}, \quad (3)$$

$$l''''_h = \sqrt{(\alpha_5 - \alpha_1)^2 + (\beta_5 - \beta_1)^2 - \left(\frac{l_w - l''''_w}{2} \right)^2}. \quad (4)$$

The unit of parameters l_w , l'_w , l'_h , l''''_h are number of pixels. In order to calculate the volume, metric unit such as mm is

Figure 5. Default parameters for under-struck state.

needed instead of number of pixels. This conversion is possible by multiplying the actual pixel size of image sensor.

3.2 Calculation of Angle between the Camera Centre Line $\overline{ZF}$ and the Bucket Line $\overline{AB}$

We can not always take the picture at the same angle. That changes the parameter values of bucket. This paper use the expression of the angle between the camera centre line and the bucket to solve this problem. This is called θ_C . This section will describe the process of calculating θ_C .

In Figure 6, let's assume that

$$r_2 = kr_1. \quad (5)$$

By the similarity between $\triangle EDD'$ and $\triangle EC'F$,

$$2a \cos \theta_c : r_1 = d : (r_1 + r_2) = d : (1 + k)r_1, \quad (6)$$

$$k = \frac{d}{2a \cos \theta_c} - 1. \quad (7)$$

In Figure 6,

$$L_1 = 2a \sin \theta_c - kr_1 = 2a \sin \theta_c - \left(\frac{d}{2a \cos \theta_c} - 1 \right) r_1. \quad (8)$$

By the similarity between $\triangle FZY$ and $\triangle FC'B$,

$$d : f = L_1 : l_2, \quad (9)$$

$$l_2 = \frac{f}{d} \left[2a \sin \theta_c - \left(\frac{d}{2a \cos \theta_c} - 1 \right) r_1 \right], \quad (10)$$

$$d : f = (1 + k)r_1 : l_1 = \frac{dr_1}{2a \cos \theta_c} : l_1, \quad (11)$$

$$l_1 = \frac{fr_1}{2a \cos \theta_c}. \quad (12)$$

l_h''' is the height of bucket in Figure 5.

$$l_h''' = l_1 + l_2 = \frac{f}{d}(2a \sin \theta_c + r_1), \quad (13)$$

$$r_1 = \frac{dl_h'''}{f} - 2a \sin \theta_c, \quad (14)$$

$$l_1 = \frac{dl_h'''}{2a \cos \theta_c} - f \tan \theta_c, \quad (15)$$

$$l_2 = l_h''' + f \tan \theta_c - \frac{dl_h'''}{2a \cos \theta_c}. \quad (16)$$

l_1 and l_2 are decided based on the centerline of the camera image. Lets assume that the ratio of l_2 and l_1 is m .

$$l_2 = ml_1, \quad (17)$$

$$l_h''' = (1 + m)l_1, \quad (18)$$

$$l_1 = \frac{l_h'''}{1 + m}. \quad (19)$$

By Eq. (15) and Eq. (19),

$$l_h''' = \frac{2af(m+1) \sin \theta_c}{(m+1)d - 2a \cos \theta_c}. \quad (20)$$

By Figure 5 and Figure 6,

$$b : d = l_w : f, \quad (21)$$

$$d = \frac{bf}{l_w}. \quad (22)$$

By Eq. (20) and Eq. (22),

$$l_h''' = \frac{2al_w f(m+1) \sin \theta_c}{(m+1)bf - 2al_w \cos \theta_c}, \quad (23)$$

$$\begin{aligned} \theta_c &= \cos^{-1} \left(\frac{\sqrt{4a^2 l_w^2 (l_h'''^2 + (m+1)^2 f^2) - b^2 l_h'''^2 (m+1)^2 f^2}}{2al_w (l_h'''^2 + f^2 (m+1)^2)} \right. \\ &\quad \left. \times f(m+1) - \frac{l_h'''^2 (m+1)bf}{2al_w (l_h'''^2 + f^2 (m+1)^2)} \right). \end{aligned} \quad (24)$$

3.3 Calculation of Angle θ_B between $\overline{AB}$ and $\overline{BD}$

In Figure 3, θ_B is fixed angle so it can be obtained by Eq. (25).

$$\theta_B = \tan^{-1} \left(\frac{c}{2a} \right). \quad (25)$$

Figure 6. Camera geometry for calculating θ_C .

3.4 Calculation of Height h between the Bucket line $\overline{AB}$ and $\overline{DH}$

θ_y can be obtained by using θ_C and θ_B .

$$\theta_y = \frac{\pi}{2} - \theta_C + \theta_B. \quad (26)$$

In Figure 7, lets assume that

$$r'_2 = k'r'_1. \quad (27)$$

The value k' can be obtained by using the similarity of $\triangle EB'H'$ and $\triangle EC'F$.

$$h \cos \theta_y : r'_1 = d' : (r'_1 + r'_2) = d' : (1 + k')r'_1, \quad (28)$$

$$k' = \frac{d'}{h \cos \theta_y} - 1. \quad (29)$$

By the similarity between $\triangle FEC'$ and $\triangle FYZ$

$$d' : f = \frac{d'r'_1}{h \cos \theta_y} : l'_2, \quad (30)$$

$$l'_2 = \frac{fr'_1}{h \cos \theta_y}. \quad (31)$$

By the similarity between $\triangle FHC'$ and $\triangle FXA$.

$$d' : f = L'_1 : l'_1, \quad (32)$$

$$L'_1 = k'r'_1 - h \sin \theta_y = \left(\frac{d'}{h \cos \theta_y} - 1 \right) r'_1 - h \sin \theta_y, \quad (33)$$

$$l'_1 = \frac{f}{d'} \left[\left(\frac{d'}{h \cos \theta_y} - 1 \right) r'_1 - h \sin \theta_y \right]. \quad (34)$$

Figure 9. Under-struck-case2.

 Figure 10. $\triangle XDC$.

$$u_2 = \frac{\pi}{2} - \cos^{-1} \left(\frac{h_l}{a} \right), \quad (56)$$

$$\text{sector } BOY = \frac{a^2}{2} \left(\theta_B + \frac{\pi}{2} - \cos^{-1} \left(\frac{h_l}{a} \right) \right). \quad (57)$$

To find the area of $\triangle XDC$, you need to find the base length and height. In Figure 10,

$$\frac{2a}{\cos \theta_B} : h_o + a \sin \theta_B = v_2 : a \sin \theta_B - h_l, \quad (58)$$

$$2a : h_o + a \sin \theta_B = v_3 : a \sin \theta_B - h_l. \quad (59)$$

By Eq. (46),

$$v_2 = \frac{a \sin \theta_B - h_l}{\sin \theta_B \cos \theta_B}, \quad (60)$$

$$v_3 = a - \frac{h_l}{\sin \theta_B}, \quad (61)$$

$$\triangle XDC = \frac{1}{2} v_3 \sqrt{v_2^2 - v_3^2} = \frac{1}{2} \tan \theta_B \left(\frac{a \sin \theta_B - h_l}{\sin \theta_B} \right)^2. \quad (62)$$

In Figure 10,

$$v_4 = a - v_3. \quad (63)$$

 Figure 11. $\triangle YOC$.

In Figure 9 and Figure 11,

$$\triangle YOC = \frac{1}{2} h_l \left(\sqrt{a^2 - h_l^2} + h_l \frac{\cos \theta_B}{\sin \theta_B} \right), \quad (64)$$

The total volume can be obtained by summing each areas.

$$\begin{aligned} V = & \frac{\pi a^2 b}{2} - \frac{a^2 b}{2} \left(\theta_B + \frac{\pi}{2} - \cos^{-1} \left(\frac{h_l}{a} \right) \right) \\ & - \frac{b h_l}{2} \left(\sqrt{a^2 - h_l^2} + h_l \frac{\cos \theta_B}{\sin \theta_B} \right) \\ & + \frac{b}{2} \tan \theta_B \left(\frac{a \sin \theta_B - h_l}{\sin \theta_B} \right)^2. \end{aligned} \quad (65)$$

3.5.3 Estimation of sand volume for under-struck-case 3 condition

The equation for obtaining the volume in under-struck-case 3 can be obtained by adding $\triangle Y'YO$ and $\triangle XY'D$ in the semi-circle-subtracted sector BYO . See Figure 12.

$$\begin{aligned} V = & V(\text{semicircle}) - V(\text{sector } BYO) \\ & + V(\triangle Y'YO) + V(\triangle XY'D). \end{aligned} \quad (66)$$

In Figure 13,

$$2a : 2a \sin \theta_B = 2a - v_5 : 2a \sin \theta_B - h, \quad (67)$$

$$\frac{2a}{\cos \theta_B} : 2a \sin \theta_B = v_6 : 2a \sin \theta_B - h, \quad (68)$$

$$v_5 = \frac{h}{\sin \theta_B}, \quad (69)$$

$$v_6 = \frac{2a \sin \theta_B - h}{\sin \theta_B \cos \theta_B}, \quad (70)$$

$$\triangle XY'D = \frac{1}{2} \tan \theta_B \left(\frac{2a \sin \theta_B - h}{\sin \theta_B} \right)^2. \quad (71)$$

In Figure 14,

$$v_8 = \sqrt{(a - v_5)^2 - (a \sin \theta_B - h)^2}, \quad (72)$$

$$v_7 = \sqrt{a^2 - (a \sin \theta_B - h)^2} - v_8, \quad (73)$$

In Figure 15,

$$u_3 = \theta_B - \cos^{-1} \left(\frac{\sqrt{a^2 - (a \sin \theta_B - h)^2}}{a} \right), \quad (76)$$

In Figure 16,

$$V$$

4. Experimental Results

Figure 13. $\triangle XY'D$.

Figure 14. Sector *BYO*-1.

Figure 15. Sector *BYO-2*.

Figure 16. $\triangle Y'YO$.

The experiment to find the focal length was done by taking a picture of an object with pre-known size at a pre-known distance. Then the focal length is found through the number of

Table 1. Focal length experiment

Length between object and camera lens (mm)	Object length (mm)	Image pixel length (pixel)	Focal length (mm)
450	113	441	19.3181
400	113	499	19.4301
350	113	559	19.0456
300	113	652	19.0407
250	113	783	19.0553
200	113	963	18.7487
150	113	1258	18.3690
Average focal length			19.0011

Table 2. Density experiment of object

Number of balls	Volume (mL)	Weight (g)	Density (g/mL)
10	1.25	2.0	1.6
20	2.5	4.0	1.6
30	3.75	6.0	1.6
40	5	8.0	1.6
Average density			1.6

Figure 17. Under-struck-case1 image.

image pixels and pre-known size and distance of the object.

The experiment to find the density of a ball was done by finding the volume and weight of a fixed number of 6 mm balls. The density is determined by dividing the weight by the measured volume.

The sand used in the experiment is a type of ball with 6mm diameter. The method to estimate the volume is as follows: The original weight is obtained through an electronic scale. Actual Volume is the volume measured when pouring water into the beaker and then pouring balls there. Estimated volume is obtained through the proposed algorithm. Estimated weight is obtained by multiplying the estimated volume by the average 1.6g/ml density obtained in Table 2.

Figure 18. Under-struck-case2 image.

Figure 19. Under-struck-case3 image.

Table 3. Experimental information

state	Grain size (mm)	Original weight (g)	Actual volume (mL)	Estimated volume (mL)	Estimated weight (g)	Error ratio (%)
case1	6	39.3	24.5	22.0	35.1	10.6
	6	39.3	24.5	23.1	36.9	6.1
case2	6	104.9	60	59.1	94.6	9.8
	6	104.9	60	65.2	104.3	0.5
case3	6	153.6	95	94.1	150.5	2.0
	6	153.6	95	105.9	169.4	10.3

The experimental results are shown in Table 3. The error rate of case 1 was 10.6% and 6.1%, the error rate of case 2 was 9.8% and 0.5%, and the error rate of case 3 was 2.0% and 10.3%. Most of errors may be from the uneven surface of the sand region made by the fixed size of ball.

5. Conclusions

In this paper, we proposed a novel method to estimate the amount of sands in the excavator bucket based on a single camera by using the image processing technique and mathematical modeling of bucket. For each of three under-struck states, a closed form of mathematical solution to estimate the sand volume of excavator bucket was implemented. The experimental results show that the error rate is within 10.6% and the minimum error rate is 0.5% in a case of under-struck-case 2.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

This research was partially supported by the MIST (Ministry of Science and ICT), Korea, under the national program for excellence in SW supervised by the IITP (Institute for Information & Communications Technology Promotion) (2016-0-00017) and partially supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2015R1D1A1A09061368) and supported by the KIAT (Korea Institute for Advancement of Technology) grant funded by the Korea Government (MOTIE : Ministry of Trade Industry and Energy) (No. N0001884, HRD program for Embedded Software R&D).

References

- [1] S. H. Ahn, S. K. Kim, and K. H. Lee, "Development of a fleet management system for cooperation among construction equipment," *Journal of the Korea Society of Civil Engineers*, vol. 36, no. 3, pp. 573-586, 2016. <https://doi.org/10.12652/Ksce.2016.36.3.0573>
- [2] F. David, P. Petr, M. Miroslav, and M. Milan, "Scanning of trucks to produce 3D models for analysis of timber loads," in *Proceedings of 17th International Carpathian Control Conference (ICCC)*, Tatranska Lomnica, Slovakia, 2016, pp. 194-199. <https://doi.org/10.1109/CarpathianCC.2016.7501092>
- [3] D. Vrablova, R. Kapica, and J. Jurman, "Methodology devising for bucket-wheel excavator surveying by laser scanning method to determine its main geometrical parameters," *Geodesy and Cartography*, vol. 38, no. 4, pp. 157-164, 2012. <https://doi.org/10.3846/20296991.2012.757438>
- [4] J. U. Won, Y. S. Chung, W. S. Kim, K. H. You, Y. J. Lee, and K. H. Park, "A single camera based method for cubing rectangular parallelepiped objects," *Journal of KIISE: Computing Practices and Letters*, vol. 8, no. 5, pp. 562-573, 2002.
- [5] Y. H. Baek and U. R. Moon, "Color edge detection using variable template operator," *International Journal of Fuzzy Logic and Intelligent System*, vol. 6, no. 2, pp. 116-120, 2006. <https://doi.org/10.5391/IJFIS.2006.6.2.116>
- [6] Xing Xiong and Byung-Jae Choi, "Comparative analysis of detecting algorithms for corner and blob features in image processing," *International Journal of Fuzzy Logic and Intelligent System*, vol. 13, no. 4, pp. 284-290, Dec. 2013.

In-Hwan Kim has been under M.S. candidate course at Dongguk university, Korea, since 2016. His current research interests include robotics and intelligent human-robot interaction.

E-mail : dlsghks199@naver.com

Dong-Woo Lim has been under M.S. candidate course at Dongguk university, Korea, since 2018. His current research interests include intelligent human-robot interaction and image processing.

E-mail : aehddn@gmail.com

Jin-Woo Jung received the B.S. and M.S. degrees in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Korea, in 1997 and 1999, respectively and received the Ph.D. degree in electrical engineering and computer science from KAIST, Korea in 2004. Since 2006, he has been with the Department of Computer Science and Engineering at Dongguk University, Korea, where he is currently a Professor. During 2001-2002, he worked as visiting researcher at the Department of Mechano-Informatics, University of Tokyo, Japan. During 2004-2006, he worked as researcher in Human-friendly Welfare Robot System Research Center at KAIST, Korea. During 2014, he worked as visiting scholar at the Department of Computer and Information Technology, Purdue University, USA. His current research interests include human behavior recognition, multiple robot cooperation and intelligent human-robot interaction.

E-mail : jwjung@dongguk.edu