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AUTOMATING BACKHOE OPERATION USING FUZZY LOGIC

DEEPAK K. SHARMA

Dept of Civil and Environmental Engineering, California State University, Fullerton, Fullerton, USA

During the past decade, automation has significantly increased in all forms of engineering. With the fast-paced research and development in automation, it is expected that automation will be commonplace and many operations will be performed using robots. Automation of heavy construction equipment is in its early stages. Attempts are persistently made to push the frontiers of science and technology to automate heavy equipment but, limited progress has been made. This research presents a fuzzy logic modeling approach for moving a back-hoe bucket from a fill point to a dump point. The fuzzy logic model is designed to accept all feasible points formed by boom and stick movements in 3D space. Inputs to the model are coordinates of fill and dump spots, as well as stick and boom dimensions. The model provides output signals to automate the bucket movement by swinging the bucket, lowering (or raising) boom, and stretching (or retracting) stick. The paper also includes three site scenarios to demonstrate the performance of the model. The three scenarios are varied from a very basic to a very complex maneuver. All three scenarios are tested for error, and the errors are within acceptable limits.

Keywords: Heavy equipment, Artificial intelligence, Excavator, Construction.

1 INTRODUCTION

Construction projects are characterized by dynamically changing site conditions. As a result, construction sites present challenges when it comes to any innovation and that has impacted the overall productivity of the industry. This is applicable to horizontal and vertical construction projects, but it is more prominent in case of horizontal construction projects like highways, canals, runways, and other similar projects. Many tasks on horizontal construction projects are executed by manually operated heavy equipment and as a result, project outcome is dependent on operators' skill. A highly competent operator will be able to lessen a cycle time as compared to an average operator (Holt and Edwards 2015). The availability of skilled operators is thus critical for overall construction industry. However, US is facing labor shortage (FRD 2018) and the issue doesn't seem to be abating soon, mandating that we seek ways to get around it.

Automation is known to improve productivity (Chen *et al.* 2018) and can also help in mitigating the impacts of labor shortage. This paper presents a fuzzy logic model for automating backhoe excavator operation. The approach will enable agencies, and equipment manufacturers to develop autonomous equipment. Using trigonometry, spherical geometry concepts and fuzzy theory, a model is here presented that aims to automate backhoe bucket movement. Model inputs consist of 3D coordinates of fill and dump points as well as stick and boom dimensions. As an output, the model provides a set of signals that will operate the excavator control joysticks. These commands will move excavator bucket from filling point to dumping point. The movement will include bucket swinging, lowering (or raising) boom, and stretching (or retracting) stick.

2 PREVIOUS STUDIES AND RESEARCH MOTIVATION

Construction productivity is lagging in terms of benefiting from technological advancements. As a result, the industry has lagged when it comes to productivity improvements in comparison to other industries (Fulford and Standing 2014). Researchers have demonstrated that construction automation can improve its productivity (Chen *et al*. 2018). While other industries have transformed into fully automated industries, construction and earthmoving operations could not be automated fully till date. Several researchers have identified challenges faced while automating earthmoving equipment (Dadhich *et al*. 2016) and these challenges require that the research community attempts to meet the automation needs.

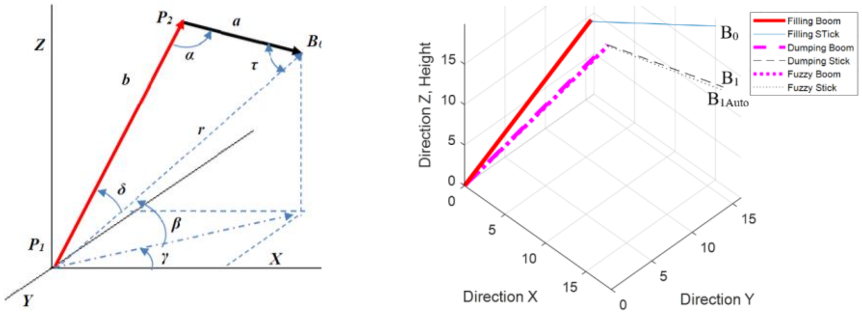
Researchers are persistently trying to push the frontiers of science and technology to make construction automation a norm (Naskoudakis and Petroutsatou 2016). A remote-controlled robotic arm has been developed that can control an equipment from a distance (Sasaki and Kawashima 2008). Similarly, a tele-operation system that enables an operator to mount the system on arm and control the excavator system remotely is also now available (Kim *et al*. 2009). Recently, the tele-operated system was equipped with additional systems consisting of head mounted display (Le *et al*. 2017). Agencies are in the process of automating construction processes. CALTRANS is developing Automated Machine Guidance (AMG) technology to improve safety, efficiency and accuracy during construction (CALTRANS 2018). On the same lines, FHWA's e-construction group reports about various technologies that use mobile phones, GPS and other advance technologies during construction. Despite these efforts, a recent review implies that equipment automation is only limited on controlling heavy equipment by remotes (Naskoudakis and Petroutsatou 2016) mandating continuous human intervention. As a result, there is a need to fully automate equipment operation. This research work builds on the previous research and presents a model for achieving comprehensive heavy equipment automation.

3 RESEARCH METHODOLOGY

A model is developed in this research that will help contemporary researchers to pursue heavy equipment automation. The model focuses on a back-hoe excavator's (excavator) displacements to move a bucket automatically. The overall process has been broken down in to small steps. As a first step, the research boundaries were created. This helped in defining the tasks and extent of this research. The second step included using feasible coordinates for filling and dumping spots followed by determining resulting angular position for excavator's boom and stick. The third step requires calculating 3-dimensional displacement for boom and stick to be able to move the bucket from fill to dump. Finally, the model outputs were analyzed to determine accuracy of the model. Scenario analysis is also included to study model performance in varying situations.

Automating excavator operation imposes variety of challenges due to its parts' movement. Boom and stick operate in coordination (swings and angularly moves) to move bucket between desired points. The bucket controls allow scooping and releasing earth. Also, crawlers move the whole excavator on ground. Considering all the activities makes the problem extremely large and complex. So, in this research the scope is restricted to the coordinated boom and stick movements along with the swinging action, thus covering many points scattered in a 3-dimensional space. The focused and limited research enables us to concentrate this paper only on one of the most unique movement seen only in excavators. The approach proposed here can be easily extended to consider bucket operations, other attachments and ground movement.

The next step focuses on locational, trigonometric and geometrical aspects of the excavator. We start with the assumption that the 3D Cartesian coordinates for fill and dump points are available. This assumption is made because accurate GPS devices are easily available and these are frequently in earthwork industry. GPS devices can be attached to the end of stick and accurate coordinates of fill and dump points can be obtained. Based on the coordinates, the angles between boom and stick are calculated. Figure 1 shows the layout of boom and stick.



(A) (B)

Figure 1. (A) Geometry and angular relations between boom and stick, (b) Base case scenario results showing the resulting fuzzy boom and stick.

P_1 represents center of the equipment with coordinates [0,0,0]. The equipment swings at point P_1 about the Z-axis and boom is hinged at P_1. Segments P_1P_2 *and* P_2B_0 represents boom and stick with dimensions b and a respectively. Point B_0 is tip of the stick where bucket is attached. Boom makes an angle θ with the XY plane. It is obtained by adding β (angle made by the resultant of boom and stick (P_1B_0) with the XY plane) and δ (angle made by the resultant P_1B_0 and boom). The projection of P_1B_0 on XY plane makes an angle γ with the positive X axis. α represents angle between boom and stick. The stick makes angle ϕ with the negative Z-direction and τ with the resultant P_1B_0. MATLAB was used to establish the relation between coordinates and angular relations of boom and stick. Calculations started with determining angular position and length of P_1B_0. Matlab's cart2sph function was used to calculate γ and β as well as distance P_1B_0 using coordinates of B_0. Cosine rule was then used to calculate the angles α, δ, τ in triangle $P_1P_2B_0$ (Eq. 1-3*)*.

$$\alpha = \mathrm{Cos}^{-1}(b^2 + a^2 - r^2)/(2ab) \tag{1}$$

$$\tau = \mathrm{Cos}^{-1}(a^2 + r^2 - b^2)/(2ar) \tag{2}$$

$$\delta = \mathrm{Cos}^{-1}(b^2 + r^2 - a^2)/(2br) \tag{3}$$

This allowed us the calculate θ (not shown in figure) as per Eq. (4):

$$\theta = \beta + \delta \tag{4}$$

Using geometrical relations, angle ϕ was obtained using Eq. (5):

$$\phi = \theta + \alpha - 90^0 \tag{5}$$

The coordinates of point P_2 were obtained by using MATLAB's sph2cart feature. This completed one set of calculation that enabled determining all the necessary geometrical details for the filling spot. Using the same steps again, angles and coordinates were recalculated for dumping spot. The dumping spot is represented as B_1 in this research. This enabled determining the stick and boom movement to move bucket from fill to dump location. All these data became input to the fuzzy model.

Fuzzy logic is an Artificial Intelligence (AI) modeling approach that allows using linguistic variables (Zadeh 1996), a property that can be conveniently applied to the current research. It is also useful when a process is complex, non-linear and operator dependent (Chen and Kairys 1993). Its ease of converting linguistic variables to desirable outputs has been exploited here to develop a fuzzy model for excavator control.

During excavation, an operator observes bucket fill and dump locations and moves the bucket between the points. The same process can be repeated through fuzzy modeling. First the visual observations are replaced by precise (crisp) coordinates. Using the geometrical relations, the locations of boom and stick are fed to the fuzzy inputs which are then fuzzified. The operator maneuver skills in fuzzy modeling are represented by several if-then rules. For example, several rules can be created that could look like *"if the dump location is too far, stretch the stick and forwarding the boom to reach the distant point*" to cover all possible scenarios. All this information collectively provided the desired outcome to be able to operate joystick controls.

The fuzzy logic model was developed in MATLAB using the approach discussed in The Basic Tipping Problem (Matlab 2017). It has three inputs and three outputs. Mamdani Fuzzy Inference System was used. The inputs included the displacements needed by boom and stick in X, Y and Z directions to move a bucket from fill to dump location. The outputs were designed to be able to provide push-pull commands for left and right joystick controls. The excavator was assumed to have standard SAE controls which means that as the left-hand joystick control is moved right the equipment swings right; left movement swings it left; forward movement pushes boom down and a pull lifts the boom up. Similarly, when the right joystick is moved forward the stick moves away and when pulled back moves the stick comes closer. All these details were used to create outputs. All inputs and outputs were assigned triangular membership function, a method detailed in Tipping Problem. Finally, validation of this approach is necessary to determine if the automated system provides acceptable outcome. Validation was done by comparing outputs from the fuzzy model with the expected outputs obtained through the trigonometric equations and geometrical relations (Eqs. (1) to (5)).

4 BASE CASE, SCENARIO ANALYSIS AND RESULTS

To test the above model a simple scenario was considered. This scenario represents an easy maneuver for an operator. In this scenario B_0 was assigned [15, 16, 19] and B_1 was assigned [18, 14, 15] coordinates. For any excavator operator this will be an easy maneuver because the overall bucket movement is 3 ft along the X direction, -2 ft along the Y direction and 4 feet in the Z direction, making a linear movement of just 5.3852 ft. Since both the points are above ground (Z coordinates are positive for both points) both points are clearly visible to operator, making it a simple maneuver. The fuzzy model developed in this research gave outputs that enabled moving the bucket from B_0 to B_{1Auto} (B_{1Auto} is the dump point obtained from the fuzzy model). The coordinates of the B_{1Auto} point came out as [18.137, 13.850, 14.792] which is very close to the desired B_1 coordinates [18, 14, 15]. The linear distance between points B_1 and B_{1Auto} represents the error and it comes out to be 0.2909 ft. Figure 1 B shows the details of this scenario in 3D view. In the figure the filling position is represented by solid lines. The thick solid line is boom and the thin solid line is stick. At some angle the dashed lines represent stick and boom reaching the dump position. The dashed lines can be observed with closely following dotted lines, representing the stick and boom reaching the dump location through the fuzzy model. Figure 1(B) shows the fill and dump spots and the corresponding boom and stick positions in a 3D view.

In the base case the overall movement of boom and stick was limited to a few feet in X, Y and Z directions. This represented a very simple maneuver. To test the model performance for some difficult scenarios the model was tested for two more scenarios representing increasingly challenging maneuvers. The results of FL model are given in Table 1.

Table 1. Results obtained using the fuzzy logic model.

Sr	Location Coordinates		Maneuver Complexity	Automatic Dump Coordinates	Error (ft)
	Pick Up	Dump			
1	[15, 16, 19]	[18, 14, 15]	Low (Base)	[18.137, 13.850, 14.792]	0.2909
2	[15, 22, 3]	[21, 5, 19]	Medium	[20.851, 4.4534, 19.436]	0.7148
3	[10, 22, -10]	[21, -18, 19]	Severe	[21.0597, -17.6105, 19.2689]	0.4771

The results indicate that the fuzzy model was able to move the bucket within a very close range of the targeted dump location. The errors in the three cases were 0.2909 ft (3.491 in) for the base case, 0.718 ft (8.616 in.) for the medium severity case and 0.4717 ft (5.6604 in.) for the extreme case. Given that the dump location will be above a dump-truck and dimension of a standard dump-truck in the US is 59×37 in^2, the maximum error of 8.616 in. can be considered acceptable. This is also considered acceptable because a human operator empties a bucket approximately above the 59×37 in^2 truck-bed and while doing so relies on visual judgement.

All these results indicate that if an excavator is provided with fill and dump coordinates and the designed fuzzy model is used, a bucket can be autonomously moved between desired locations. Repeating this several times will enable autonomous earth moving. While the current system does not include bucket and crawler operation, the learning from this paper can be extended to include bucket and crawler in the model. Having a fully automated excavator will have significant impact on productivity and safety.

5 CONCLUSIONS

Automating heavy equipment has a tremendous opportunity but a very limited advancement could be seen in terms of fully automating heavy equipment. Through this paper, a fuzzy logic model is proposed for automating excavator operation. The insights gained through this work can be extended to other excavation operations and equipment. This work will enable researchers, agencies and equipment manufacturing companies to pursue fully automated equipment.

The results of the research showed that fuzzy logic modeling enabled automating excavator operation. This was demonstrated by the fact that the model was tested for three scenarios and gave good results. Visually, the results are very good and the automated excavator will be able to move a bucket autonomously. The results are comparable to the work by other researchers (Shi *et al*. 1996). The authors used fuzzy logic to operate a dozer replica and the trajectory of equipment was analyzed. Similarly, in this research the visual analysis (Figure 1B) indicates a very good outcome. Quantitatively the error ranged from 3.491 in. to 8.616 in. which is acceptable considering the size of equipment employed on excavation sites. The errors are likely due to the suboptimal membership function design. Additional research, which will be largely based on trial and error and thus could be intensive, is expected to improve the results further.

Based on the findings of this research it is expected that researchers extend this excavator problem by including bucket operation and movement on ground. Future researchers will be able to build upon this work by considering other heavy equipment for automation. An immediate application is to automate front shovels and cranes. From an application perspective, it is suggested that the automation model be extended further and used for on mass earthwork sites such as canals, dams, highways and others. At an initial phase these excavators can work as a part of other equipment fleet where the fleet is dumping dirt near an automated excavator and the excavator keeps repeating the loading operation. Such a deployment will enable studying the model's real-life performance and improve it. The deployment is expected to improve on-site productivity and thus enable meeting the project's overall goals efficiently.

5.1 Future Works

The modeling approach discussed in the paper provides a basic groundwork that can be pursued further and one of them is productivity. Automating backhoes will have a noticeable impact on productivity because the operations will be very precise. An operator maneuvers a backhoe by moving the left joystick forward and backward to move the boom down and up respectively. Similarly, moving right joystick forward and backward moves the stick away and brings it closer respectively. Manual control of the joysticks will move bucket along a non-linear path and thus it takes more time than a movement on a linear path. As a result, the production will increase, because, as per Peurifoy *et al.* (2011) the basic production is inversely proportional to cycle time and thus any reduction in the cycle time will increase the overall productivity of the backhoe.

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