

Energy Saving in an Autonomous Excavator via Parallel Actuators Design and PSO-Based Excavation Path Generation [†]

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Abstract: An autonomous excavator can be a good solution in the construction industry to deal with existing issues such as high labor costs and harsh and hazardous environmental conditions. To increase energy efficiency for autonomous excavators, this study proposes two approaches. First, a new and unique design with parallel arm and bucket actuators is proposed for an electric excavator manipulator. Since the three actuators of the boom, arm, and bucket are in series for the conventional design of excavators, it is difficult to share external loads between them. However, a parallel configuration of the arm and bucket actuators in the proposed new design can facilitate load sharing and overcome higher external loads. By replacing hydraulic actuators with electric linear actuators, this design also reduces energy consumption during idling. Moreover, with low back drivability, the electric linear actuators can handle relatively high external forces without spending energy while not in motion. Secondly, a PSO-based path-generation algorithm was developed for autonomous excavation to minimize energy consumption while avoiding collisions with unwanted obstacles. In the PSO algorithm, it is possible to change the priorities of the elements to the minimum by adjusting the gains in the cost function. Two scenarios—scenarios with and without considering energy saving—were considered to test the performance of the developed algorithm, with the results between the scenarios compared. Simulation results show that the proposed algorithm reduces energy consumption in each digging cycle by 18.51%.

Keywords: autonomous excavator; parallel actuators design; PSO-based path generation

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1. Introduction

An excavator is one of the most useful machines in the construction industry, which can perform various difficult tasks. However, the operations involving excavators require highly skilled operators, resulting in high labor costs. Furthermore, in some cases, the excavators are exposed to hazardous conditions, which increases the risk to operators. Therefore, there has been a growing interest in the transition from human operators to autonomous excavators in the construction sector. Autonomous excavators do not require an operator on the site, and one person can supervise several machines remotely by scheduling the required tasks and monitoring their performance [1]. These machines are capable of working all the time except for the time they take to replenish energy resources. As a result, this autonomy will provide us with significant time and cost savings in the long run. Recently, global warming and the shortage of fossil fuels have increased the demand for electric vehicles and machines [2,3]. Excavators also consume a large amount of energy to complete their required tasks [4,5], and the pump in hydraulic excavators is always working, even when the engine is idle. Therefore, energy during idle time needs to be reduced [6]. Furthermore, a considerable amount of energy is wasted through hoses,

valves, and connectors in hydraulic excavators [7]. In light of the above reasons, one possible solution to save more energy in excavators would be to use electric actuators that do not require hoses or valves, thereby avoiding energy loss. Additionally, a linear electric actuator has small back drivability [8]. Therefore, it keeps the excavator in its position without consuming energy when idling under the external load.

However, the load capability of electric actuators is lower than hydraulic ones in general [9]. To tackle this issue, our study selected linear electric actuators with lead screws as an actuator type for the new design of an excavator. In this way, it is possible to handle the same load with a lower-capacity (or smaller) electric actuator while saving energy at the same time. Because excavation trajectories also affect energy consumption, researchers have provided different approaches to path planning for autonomous excavation. In this study, paths for the bucket tip using the Particle Swarm Optimization (PSO) algorithm [10] have been generated to reduce the excavator's energy consumption while minimizing the distance between a generated path and the desired path. In addition, the proposed path-generation algorithm is able to avoid collisions with any detected obstacles in the ground.

2. Methodology

2.1. Design

In this paper, the primary objective of designing a new excavator is to achieve a lower load on actuators and a larger workspace. A key difference between the conventional excavator and this design lies in the use of two actuators in parallel. This configuration permits load sharing between them. In the conventional excavator design, as illustrated in Figure 1, there are three actuators on its manipulator, working in series. This means that they are not cooperating to share external loads. However, the arm and bucket actuators in the proposed new design are working in parallel to balance out the loads, as seen in Figure 2.



Figure 1. The conventional CAT mini excavator [11].

Through several trials, the final design (Figure 2) was chosen to meet two criteria simultaneously (i.e., a lower load on the actuators and larger workspace). This design allows for a relatively acceptable workspace and less load on the actuators by distributing the applied load from the ground to both the bucket and arm actuators.

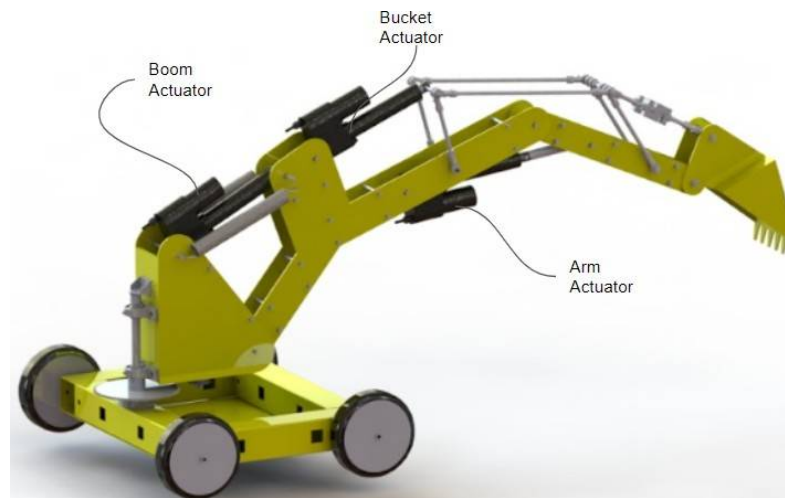


Figure 2. Accepted final design.

2.2. Optimal Path-Generation Method

Besides the design change, a PSO algorithm-based optimal path-generation method is proposed as an additional approach to minimize energy consumption for an autonomous excavator. For this method, the excavator bucket was considered to behave like a mobile robot, which can move in 2D directions (x , y) and rotate around one axis (z). The boom, arm, and bucket linear actuators are used to control these three DOFs (degrees of freedom). Figure 3 illustrates the similarities between the bucket and a mobile robot.

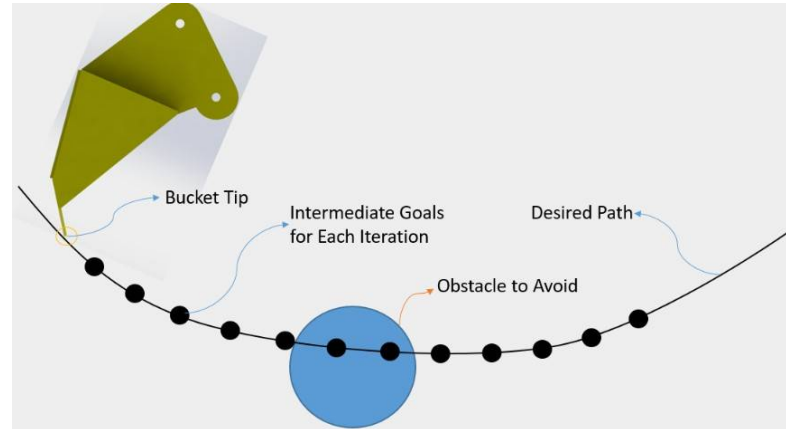


Figure 3. Similarities between the bucket and a mobile robot.

Similar to a mobile robot, the excavator bucket follows the desired path while avoiding a collision with obstacles. However, energy saving was included as an additional consideration to generate the desired path. As shown in Figure 4, the robot reached its desired destination (goal), avoided obstacles, and tried to minimize energy consumption. As defined in Equation (1), the cost function for the applied PSO takes into account three components (i.e., the shortest path to the goal, obstacle avoidance with minimal deviation from the desired path, and minimum energy consumption). When the cost function is minimized, a better solution (i.e., the optimal path) is generated.

$$Cost = W_1 \times Goal\ Distance + W_2 \times \left(\frac{1}{Object\ Distance} \right) + W_3 \times Energy \quad (1)$$

where W_1 , W_2 , and W_3 are gains that are selected based on the priority between the three criteria.

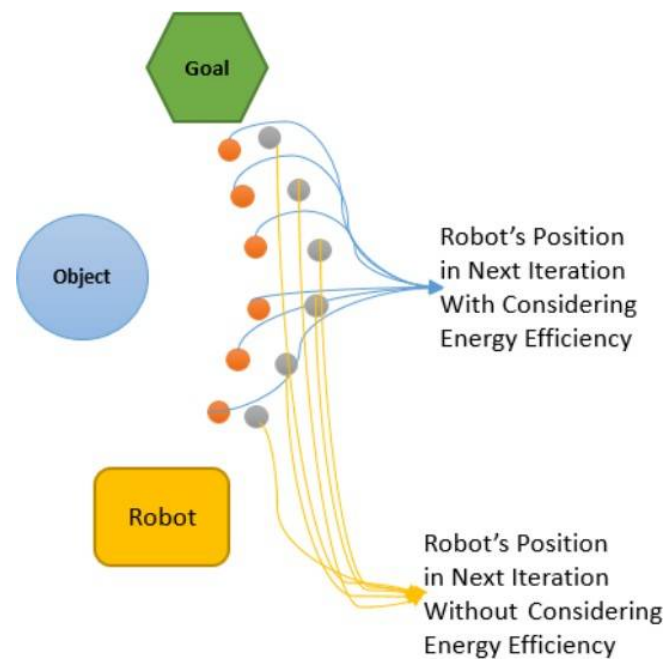


Figure 4. The PSO-based motion-generation method for the robot.

3. Results

3.1. Design

To compare the load distribution along three actuators between the new and the conventional designs, both hydraulic and electric excavators were set to have identical joint angles, as seen in Figure 5.

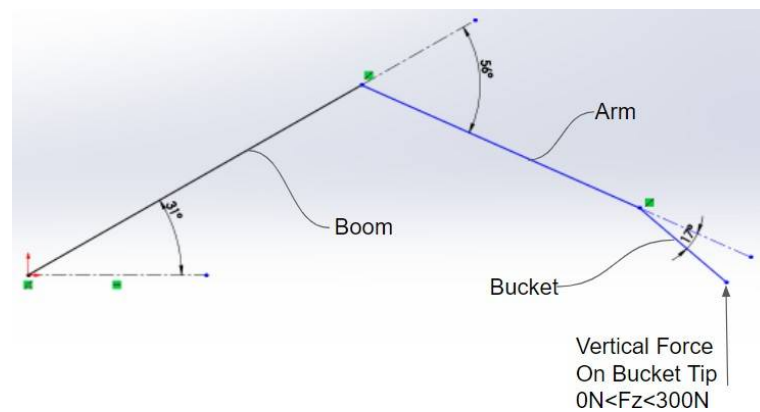


Figure 5. The selected posture to study the load on each actuator.

Specifically, the relative angle between the boom link and the horizon is 31 degrees, the relative angle between the arm and the boom links is 56 degrees, and the relative angle between the bucket and the arm links is 17 degrees. Then, the vertical upward load on the bucket was increased gradually from 0 to 300 N in order to analyze the distributed load on each actuator between the two designs (see Figure 6).

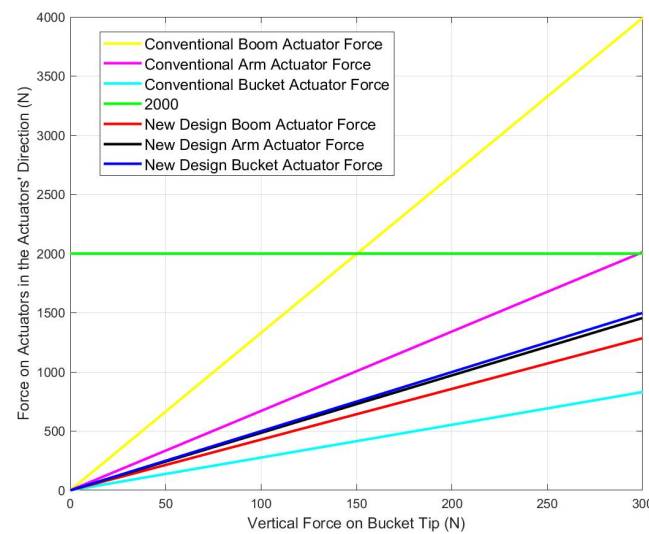


Figure 6. The comparison of results of the load simulation between the conventional and the new designs.

In this simulation, 2000 N was considered to be the maximum capability of each actuator. The results show that in the conventional design, the boom and the arm actuators experience loads exceeding 2000 N. However, none of them reach this limit in the new design. The structural merit in the proposed design allows the excavator to adopt lower-capacity electric actuators for the same amount of a vertical load, therefore saving more energy. As the second design criterion, the workspace covered by a three-link manipulator is compared between the conventional and new designs in Figure 7.

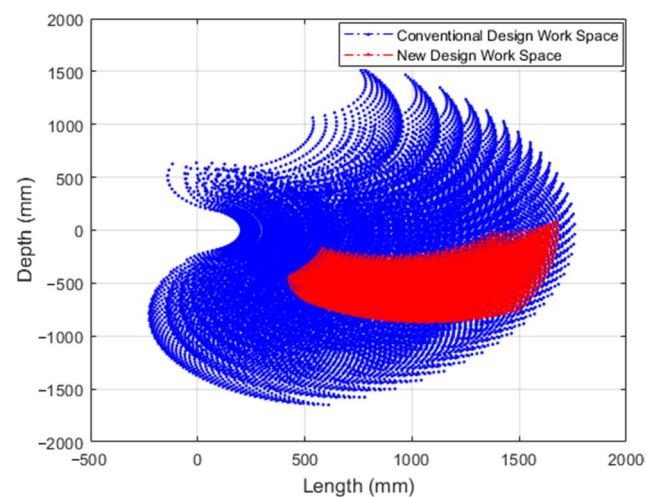


Figure 7. Comparison between the new and conventional design workspaces.

Although the workspace for the new design is less than the conventional design, it is still sufficient to carry out the normal required excavation tasks.

3.2. Optimal Path Generation Method

To evaluate the effect of the developed path-generation method in terms of energy saving, simulations were carried out under two different scenarios (i.e., with and without considering the energy-saving component). In the first scenario (Figure 8a), energy-saving is not taken into account, and thus the gain of W_3 in the cost function is set to zero. In the second scenario (Figure 8b), the excavator performs the same task as the first scenario, but it also tries to minimize energy consumption (i.e., not zero of W_3). In both scenarios,

the excavator attempts to move the bucket along the desired path without contacting the ground. In the first scenario, the total energy consumed for one cycle of digging path is 81 J and the maximum deviation between the generated path and the desired path is less than 2 mm. In the second scenario, the total consumed energy drops to 66 J, with a reduction of 18.51%, but the deviation between the generated path and the desired path is slightly increased (maximum deviation: 11 mm). However, it can be considered within an acceptable range of error.

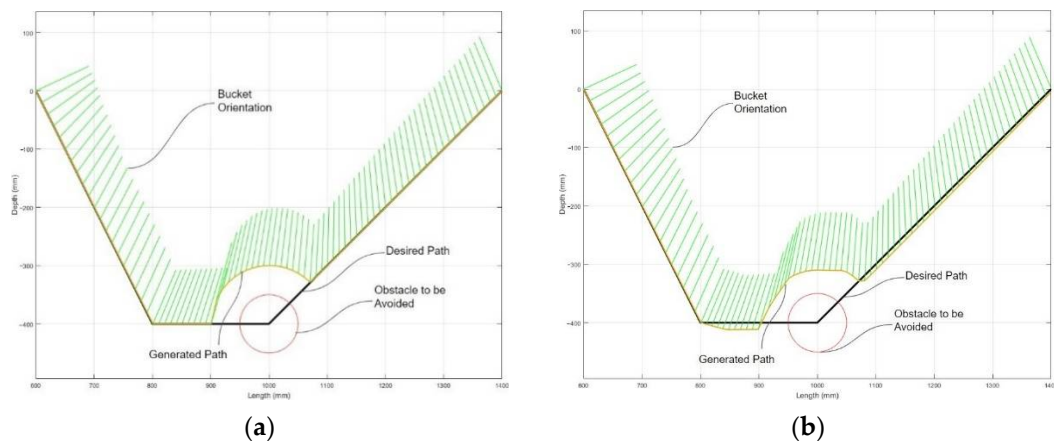


Figure 8. Motion-generation simulation: (a) without considering the energy saving; (b) with considering the energy saving.

4. Conclusions

The objective of this study is to propose a new design for an electric excavator with linear lead screw actuators that takes advantage of low back drivability to save energy during idling time. Particularly, the parallel structure between the linear actuators in the new design allows for a reduction in the load distribution on them by more than 50%. As an additional energy-saving strategy, a new approach for path generation of autonomous excavators is proposed. This approach adopts the PSO algorithm that considers the desired path, obstacle avoidance, and minimum energy consumption simultaneously. Simulation results indicate that the proposed path-generation algorithm can reduce the energy consumption for one cycle of digging path by 18.51%. In the next step, the findings from the simulations will be experimentally validated using a test platform constructed based on the proposed design.

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