

Collaborative Tracking Control Strategy for Autonomous Excavation of a Hydraulic Excavator [†]

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Abstract: A hydraulic excavator consists of multiple electrohydraulic actuators (EHA). Due to uncertainties and nonlinearities in EHAs, it is challenging to devise a proper control strategy. This paper provides a collaboration of PID and fuzzy controllers to successfully overcome the aforementioned difficulties. A major goal of the control design is to minimize tracking errors of the bucket tip position for autonomous excavation. Co-simulation models including control algorithms and hydraulic components were created using Matlab and Amesim to validate the performance of the designed controllers. Simulations indicate that the proposed method enables achieving accurate tracking control for autonomous excavation with small tracking errors despite the nonlinear characteristics of the hydraulic excavator system.

Keywords: autonomous excavation; PID; fuzzy logic; tracking control; electro-hydraulic actuator

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1. Introduction

Hydraulic excavators are widely used in construction sites for ground leveling, digging, trenching, etc. Some of these tasks can be handed over to an autonomous excavator that is capable of doing these frequent and repetitive tasks with a high degree of accuracy. Therefore, accurate tracking of the desired trajectory is a crucial component of autonomous excavation.

In a hydraulic excavator (Figure 1), three main hydraulic cylinders control the movement of the arm by converting fluid energy into linear motion. However, uncertainties and nonlinear behaviors of these hydraulic actuators always make it challenging to design a proper control strategy for successful excavation. To solve the aforementioned problem, different control schemes have been suggested by researchers.

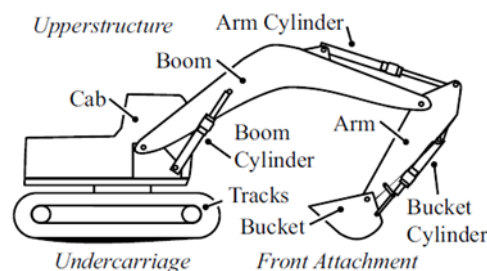


Figure 1. Hydraulic excavator and its main components [1].

The author in [2] presents an improved particle swarm optimization algorithm to tune the gains of PID controllers for the nonlinear cylinder systems for an excavator. The study in [3,4] applied adaptive non-linear PI control and cross-coupled precompensation.

In hydraulic actuator control designs, [5,6] used fuzzy logic to auto-tune the PID and sliding mode parameters, respectively while [7] employed deep reinforcement learning.

This paper proposes a tracking control strategy with a combination of PID and fuzzy control that can handle the uncertain and nonlinear characteristics of hydraulic actuation systems in excavators and minimize tracking errors of the bucket tip for autonomous excavation. The performance of the proposed control algorithms was evaluated by a co-simulation in multi-physics domains using MATLAB Simulink and Amesim software. The remainder of the paper is organized in the following manner. Section 2 describes the system modeling for an excavator. In Section 3, the designed controllers are presented. Section 4 provides an established co-simulation model. In Section 5, validation results through a co-simulation are presented. Finally, concluding remarks are provided.

2. System Modeling

The excavator system was modeled using two sub-parts that include hydraulic and kinematic models as follows.

2.1. Hydraulic Circuit Modeling

The hydraulic system was modeled in the Amesim software. The hydraulic components considered for the modeling include a power source, 3 position/4-port hydraulic servo valves, a tank, and double-acting hydraulic cylinders. Figure 2 illustrates an example hydraulic circuit of one cylinder modeled in Amesim software, and Table 1 presents the parameters used for the simulation.

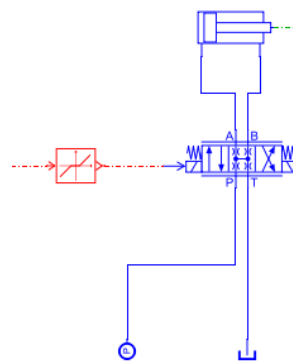


Figure 2. Hydraulic circuit of one cylinder modeled in Amesim.

Table 1. Parameters used for the simulation.

| Symbol | Parameter | Value |
|------------|---|----------------------|
| Dp | Piston diameter | 70 mm |
| DR | Rod diameter | 40 mm |
| Ls | Stroke length | 1000 mm |
| Vd | Cylinder dead volume | 50 cm ³ |
| IV | Valve rated current | 590 mA |
| ω | Valve natural frequency | 80 hz |
| δ | Valve damping ratio | 0.8 |
| Qn | The nominal flow rate of the valve at maximum opening | 79 $\frac{lit}{min}$ |
| Δp | Corresponding pressure drop | 14 bar |

2.2. Kinematic Modeling

The inverse kinematics equations in Equations (1)–(3) for the bucket tip’s motion were solved analytically, which are required for the contour control design. The following Equations (1)–(3) represent the x and y positions and the angle of the bucket tip.

$$x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3), \tag{1}$$

$$y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) + L_3 \sin(\theta_1 + \theta_2 + \theta_3), \tag{2}$$

$$\alpha = \theta_1 + \theta_2 + \theta_3 \tag{3}$$

where x and y are the bucket tip’s position in x and y direction. α is the bucket tip’s angle in workplane. L_1 , L_2 , and L_3 are the lengths of the arm, boom, and bucket links, respectively. Also, θ_1 , θ_2 and θ_3 are the angles of the arm, boom, and bucket joints.

By substituting Equation (3) into Equations (1) and (2) and solving the inverse kinematics of a two-link serial manipulator with Equations (1) and (2) (i.e., only L_1 and L_2 links remain), the first two angles can be determined. Then, the third joint angle can be derived using Equation (3).

3. Control

Figure 3 depicts the designed control scheme that consists of contour and cylinder controllers. The PID-based contour control was designed to compensate for the misplacement of the bucket tip on the working plane, and thus can contribute to minimizing tracking errors. The fuzzy-logic cylinder control was adopted to maintain the desired stroke of each EHA by adjusting the position of servo valves. This control allows for tracking control during excavation operations due to its capability to deal with highly nonlinear and uncertain dynamics of the hydraulic components.

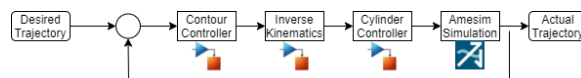


Figure 3. Block diagram of the proposed control design.

3.1. Contour Controller

As shown in Figure 4, there is always a difference between the desired trajectory of a bucket tip and the actual one during excavation. The tracking error can be compensated by calculating the required stroke deviation in each EHA using the inverse kinematics equations. However, in this study, two sets of control strategies were applied to reduce the tracking error.

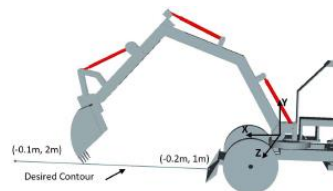


Figure 4. An example for the desired trajectory (contour) of a bucket tip [4].

In the study, three PID controllers were added to each error of the bucket tip’s x position, y position, and angle. By doing so, the misplacement of the bucket tip in each axis can be independently compensated by reflecting the actual position, and thus allowing accurate contour tracking. The block diagram of the designed PID contour control is shown in Figure 5.

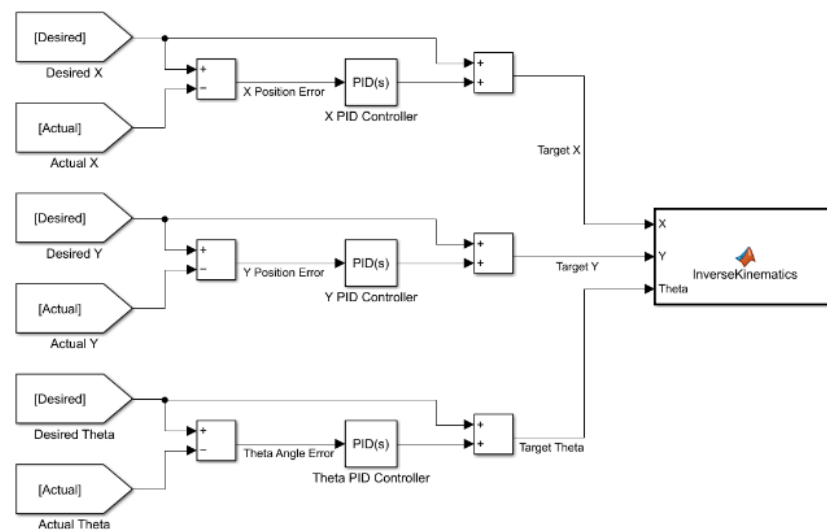


Figure 5. Schematic of contour error compensation.

3.2. Cylinder Position Control

The fuzzy logic was considered for each cylinder’s position control to handle the highly non-linearity of the EHAs. The fuzzy logic controller does not need a mathematical model of the system to achieve desired system outputs [8] and this is effective in controlling hydraulic actuators with high nonlinearities and uncertainties.

Figure 6 represents the fuzzy reference (a) and the membership functions for inputs (b) and an output (c) for the proposed fuzzy controller.

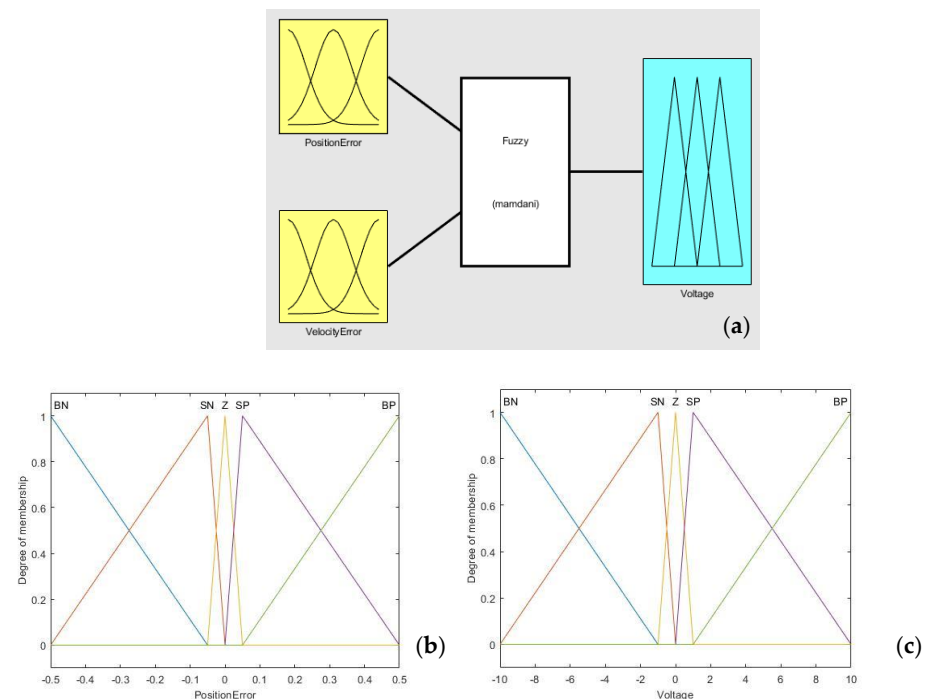


Figure 6. Components of the designed fuzzy controller: (a) Fuzzy inference engine; (b) Membership function for inputs; (c) Membership function for output.

3.2.1. Inputs and Outputs

The designed controller has two inputs: position error and velocity error. The position error is defined as the signed difference between the desired position and the actual

position of each hydraulic actuator. The defined velocity error is the signed difference between the desired velocity of each hydraulic actuator and its actual velocity. The control output is the voltage signal applied to the servo-valve.

3.2.2. Input and Output Fuzzifier

To fuzzify the input values, a set of membership functions need to be defined. In this paper, five sets of triangular membership functions are used as each input’s fuzzifier. The membership functions are categorized as big negative (BN), small negative (SN), zero (Z), small positive (SP), and big positive (BP) according to the amount of error (see Figure 6b). Just as with the input variables, the fuzzification of the output variable (voltage to the electro-valve) can be achieved with five triangular membership functions as seen in Figure 6c).

3.2.3. Fuzzy Inference System and Defuzzification

For the fuzzy inference system, the Mamdani method was selected. We used the min method for both ‘And’ and ‘Implication’ and the max method for both ‘Or’ and ‘Aggregation’. As the output of the fuzzy inference system is a fuzzified set, it must be converted to a numerical value by defuzzification. The centroid method was chosen for the defuzzification in this study.

3.2.4. Rules

As the designed fuzzy controller contains two inputs each of which has five membership functions. Thus, a total of 25 rules must be defined. Table 2 shows the defined rule sets.

Table 2. Fuzzy rule set table.

| | | Position Error | | | | |
|-----------------------|-----------|-----------------------|-----------|-----------|-----------|-----------|
| | | <i>BN</i> | <i>SN</i> | <i>Z</i> | <i>SP</i> | <i>BP</i> |
| Velocity Error | <i>BN</i> | <i>BP</i> | <i>BP</i> | <i>BP</i> | <i>Z</i> | <i>Z</i> |
| | <i>SN</i> | <i>BP</i> | <i>BP</i> | <i>SP</i> | <i>Z</i> | <i>SN</i> |
| | <i>Z</i> | <i>BP</i> | <i>SP</i> | <i>Z</i> | <i>SN</i> | <i>BN</i> |
| | <i>SP</i> | <i>SP</i> | <i>Z</i> | <i>SN</i> | <i>BN</i> | <i>BN</i> |
| | <i>BP</i> | <i>Z</i> | <i>Z</i> | <i>BN</i> | <i>BN</i> | <i>BN</i> |

3.2.5. Co-Simulation

The hydraulic components for an excavator were modeled using Amesim software that allows modeling multi-domain physical systems such as hydraulic, mechanical, control, and other systems. Additionally, it allows the creation of more realistic simulation models, particularly for hydraulic applications with inherent nonlinearity and complex behavior. Finally, since it provides a co-simulation interface with Matlab/Simulink in which the developed control algorithms were designed. Therefore, a more accurate control validation can be achieved when compared to separate simulations for a coupled system (multi-domain physical systems), such as an excavator.

The Simulink model generates the voltage signals to drive servo valves and the Amesim model operates the hydraulic components and mechanical manipulators based on those signals. After that, the feedback from Amesim is used to send the new voltage signals. Figure 7 represents the co-simulation model in Amesim software.

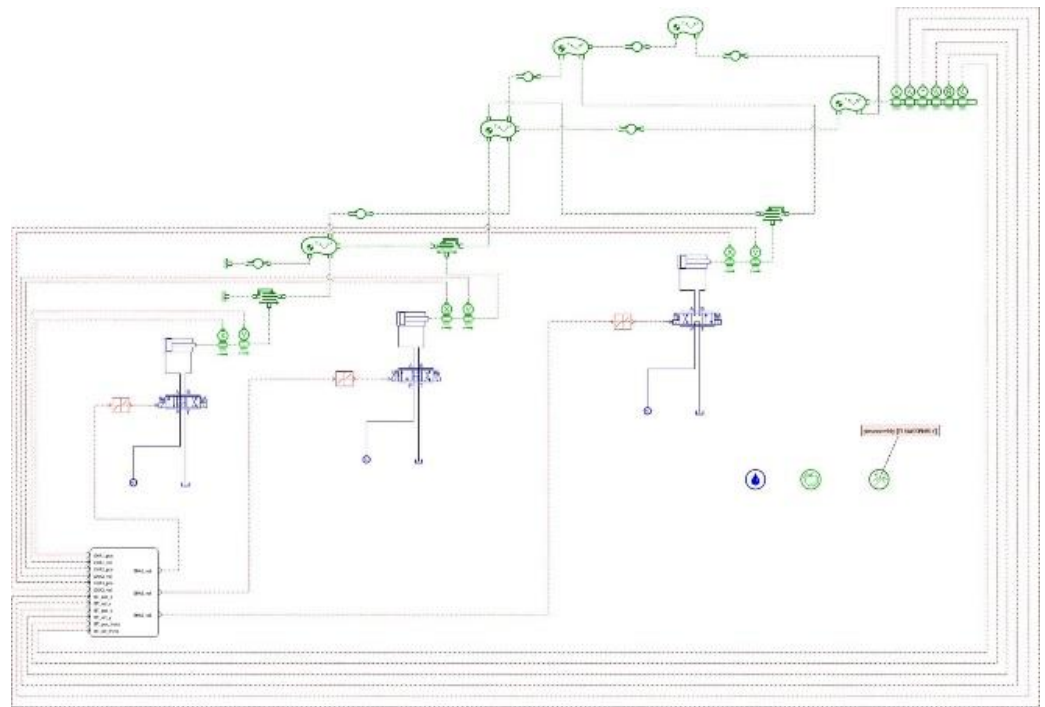


Figure 7. Cosimulation model in Amesim software.

4. Results

Figure 8 presents simulation results that include the desired trajectory (blue) and actual tracking response (red) in the bucket tip’s x position, y position, and angle.

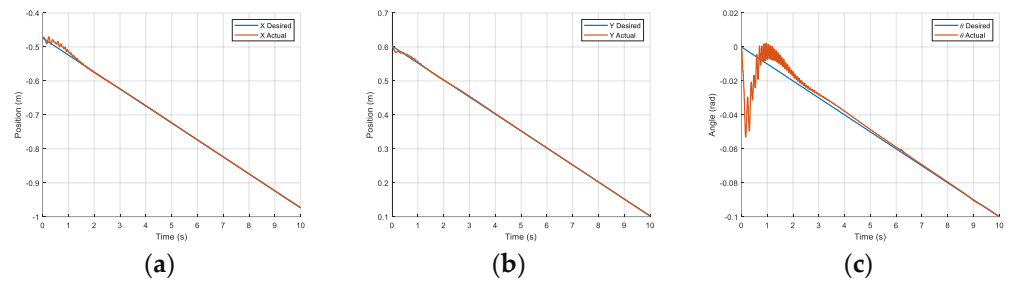


Figure 8. Tracking results: (a) x -axis; (b) y -axis; (c) theta.

As shown, the proposed controllers demonstrate satisfactory performance following the desired trajectory in each direction. Although initial vibrations and chattering are observed due to the initial establishment of the hydraulic actuators, they disappear and all responses become stable after 2 s.

5. Conclusion

To overcome nonlinear behaviors of the hydraulic actuators in excavators and improve tracking accuracy for autonomous excavation, this paper proposes a collaborative tracking control strategy that incorporates the PID-based contour control and fuzzy position control. To validate the performance of the developed controllers, a multi-domain simulation model was created for co-simulations, which includes the control algorithms and the excavator’s mechanical and hydraulic systems designed in Matlab and Amesim, respectively. Simulation results confirm that the proposed control strategy provides high tracking accuracy by combining contour error compensation with cylinder position control. Moreover, decoupling the control algorithms into two layers of position and contour allows for independent tuning and an easier control design process.

Institutional Review Board Statement:

Informed Consent Statement:

Data Availability Statement:

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