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A Fuzzy-Proportional–Derivative Controller for Nonlinear and Underactuated Overhead Crane Systems: Design, Simulation, and Performance Evaluation

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Abstract: This paper presents the design and simulation of a Fuzzy-Proportional–Derivative (Fuzzy-PD) controller for a nonlinear and underactuated overhead crane system. The proposed method aims to achieve rapid trolley positioning and effective suppression of payload swing under strong nonlinear coupling and parameter uncertainties. The controller combines the adaptive reasoning of fuzzy logic with the fast transient characteristics of a PD structure by using position error and its rate of change as input variables. The fuzzy inference system is constructed with triangular membership functions, a symmetric 5×5 rule base, and MAX–PROD inference with centroid defuzzification. The control output is generated incrementally and integrated to ensure smooth actuation. MATLAB/Simulink simulations demonstrate that the Fuzzy-PD controller achieves accurate position tracking with a short settling time of 3–5 s, minimal steady-state error, and payload oscillations below 0.1 rad. The control force remains bounded within ±3 N, confirming stability and energy efficiency. Compared with conventional PID and classical fuzzy controllers, the proposed approach provides faster transient response, improved damping, and enhanced robustness, making it a simple yet effective control solution for real-time overhead crane applications.

Keywords: *Overhead Crane System, Fuzzy Logic Control, PD Controller, Nonlinear Dynamics, Swing Suppression, Intelligent Control.*

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I. INTRODUCTION

➢ *Introduction*

The overhead crane system represents a classic example of a nonlinear and underactuated mechanical system widely used in industrial material handling and automation. It consists of a trolley moving horizontally along a track while carrying a suspended payload that behaves dynamically like a pendulum. The main control objective is to move the trolley to a desired position while suppressing payload oscillations. However, strong nonlinear coupling between the trolley motion and the swinging payload makes this system highly challenging to control. Moreover, the system dynamics are affected by several uncertainties, including variations in payload mass, cable length, and external disturbances such as friction and wind. These nonlinear characteristics make the overhead crane system an excellent benchmark for testing advanced control algorithms.

Conventional controllers such as PID, LQR, and state feedback methods have been extensively applied to overhead cranes, but their performance often degrades under strong nonlinearities and parameter variations (Benhidjeb & Gissinger, 1995). To address these issues, Fuzzy Logic Control (FLC) has emerged as a powerful approach for controlling uncertain and nonlinear systems without requiring an accurate mathematical model. The FLC framework relies on linguistic rules and fuzzy inference mechanisms that emulate human reasoning, allowing it to handle complex nonlinearities and external disturbances effectively. Previous research on nonlinear systems such as the ball and beam (Vu & Tamre, 2018; Nguyen, 2023) and inverted pendulum (Ismail, 2013; Magaña & Holzapfel, 1998) has demonstrated

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the advantages of FLC in stabilizing highly unstable and underactuated systems. These studies have confirmed that FLC provides smoother control action, stronger robustness, and faster transient response compared to classical controllers.

In the domain of overhead crane control, several researchers have successfully integrated fuzzy logic into different control architectures. Early studies by Szpytko and Smoczek (2008) and Smoczek and Szpytko (2010) proposed fuzzy-based and neuro-fuzzy adaptive controllers for crane positioning and load swing suppression, demonstrating superior robustness and human-machine adaptability. More recently, Esleman et al. (2021) designed a hybrid fuzzy-PID controller optimized by the Bees Algorithm, achieving improved positioning accuracy and oscillation damping. Similarly, Pham et al. (2022) developed an adaptive fuzzy hierarchical sliding-mode controller for a six-degrees-of-freedom overhead crane, demonstrating effective compensation of nonlinear coupling and payload swing. Fu et al. (2023) introduced a fuzzy-PID controller optimized via the Stray Lion Swarm Optimization algorithm, while Zhang et al. (2024) proposed a variable-universe fuzzy-PID controller using the Improved Sparrow Search Algorithm (ISSA) to enhance control precision and adaptability. These recent developments highlight the trend toward hybrid fuzzy-optimization frameworks that combine interpretability with adaptive performance for complex nonlinear crane systems. Furthermore, Huang (2019) provided a comprehensive survey confirming the increasing effectiveness of fuzzy-based systems in nonlinear and uncertain environments.

Despite these advancements, designing an effective fuzzy logic controller for the overhead crane remains a challenging task due to the system's strong nonlinear coupling and underactuated dynamics. To overcome these difficulties, this study develops a fuzzy logic–based control strategy capable of achieving rapid trolley positioning, smooth transient response, and effective payload swing suppression under parameter uncertainties and external disturbances. The proposed controller is modeled ands validated through MATLAB/Simulink simulations, and its performance is compared with conventional PID control to demonstrate the superior capability of FLC in handling nonlinear coupled dynamics.

➢ *The Main Contributions of this Study can be Summarized as Follows:*

- Designing a fuzzy logic controller to suppress payload oscillations and improve position tracking performance of the overhead crane system.
- Developing optimized fuzzy membership functions and rule bases to achieve smooth control and minimal settling time.
- Evaluating the robustness and adaptability of the proposed controller under varying payload conditions and external disturbances.

II. RELEVANT THEORY

A. *The Ball and Beam System*

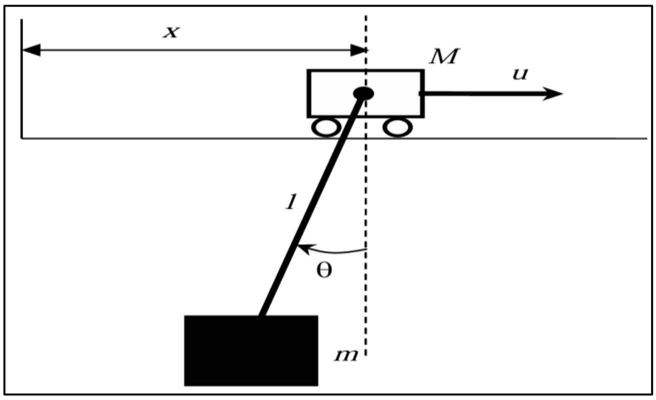

Fig 1 Diagram of Overhead Crane System

➢ *Mathematical Model*

The overhead crane is a classical nonlinear and underactuated mechanical system that exhibits coupled translational and pendulum-like rotational dynamics. Structurally, the system consists of a trolley of mass Mthat moves horizontally along a rail and a suspended payload of mass $m$attached to the trolley by a rigid massless cable of length l. The control input $u(t)$represents the horizontal driving force acting on the trolley, while the payload swing is characterized by the angular displacement $\theta(t)$relative to the vertical direction, as shown in Figure 1.

Due to gravity, the payload behaves dynamically as a pendulum, and its motion is strongly coupled with the horizontal displacement of the trolley $x(t)$. Any acceleration of the trolley induces a pendulum swing, while the pendulum's motion also influences the horizontal force acting on the trolley. This mutual coupling introduces significant nonlinearities and underactuation into the system.

Applying Newton–Euler or Lagrangian mechanics to both the trolley and the payload yields the coupled nonlinear equations of motion as:

$$\ddot{x} = \frac{u - ml\dot{\theta}^2 \sin\theta - mg\sin\theta\cos\theta}{(M+m) - m(\cos\theta)^2}$$

$$\ddot{\theta} = \frac{-u\cos\theta + mg\dot{\theta}^2\sin\theta\cos\theta + (M+m)g\sin\theta}{(ml(\cos\theta)^2 - (M+m)l)}$$

Where:

M: mass of the trolley [kg]

m: mass of the payload [kg]

l: length of the cable [m]

g: gravitational acceleration [m/s²]

$u(t)$: horizontal control force acting on the trolley [N]

$\theta(t)$: swing angle of the payload relative to the vertical [rad]

These two second-order nonlinear equations describe the dynamic interaction between the trolley motion and the pendulum swing. The first equation represents the horizontal dynamics of the trolley, which is affected by the pendulum's angular velocity and gravity components. The second equation represents the pendulum's angular motion, which depends on the trolley acceleration and the gravitational restoring torque.

➤ *Dynamic Characteristics*

- *Nonlinear Dynamics*

The overhead crane exhibits strong nonlinear coupling between the trolley's translational motion and the payload's oscillatory behavior. The terms $\sin\theta$, $\cos\theta$, and the quadratic term $\dot{\theta}^2$introduce nonlinearities, while the mutual dependence between $x$and θcreates underactuation. This nonlinear interaction makes the system difficult to control using conventional linear methods.

- *Instability*

The system is inherently unstable when the trolley accelerates rapidly, as this can amplify payload swing. Moreover, without feedback control, the oscillatory motion persists due to the absence of natural damping, requiring active control strategies to stabilize both the trolley position and the payload swing simultaneously.

- *Control Objective*

The primary control goals are:

✓ To move the trolley to the desired position accurately.
✓ To minimize or suppress the payload swing during and after motion.

These objectives must be achieved under nonlinear, coupled dynamics and parameter uncertainties.

This nonlinear model serves as the foundation for designing intelligent control strategies such as Fuzzy Logic Control (FLC), adaptive, or sliding-mode approaches, which can handle the underactuated nature and nonlinear coupling of the overhead crane system effectively.

B. *Fuzzy-PD Controller*

The overhead crane system, being a nonlinear and underactuated mechanical structure, represents an ideal application for intelligent control methods such as fuzzy logic. The coupling between the trolley's horizontal motion and the pendulum-like swing of the suspended load introduces complex nonlinear interactions that challenge conventional linear control approaches. To overcome these limitations, a Fuzzy-Proportional–Derivative (Fuzzy-PD) controller is implemented. Unlike a conventional fuzzy logic controller (FLC) that directly maps the system states to control outputs, the Fuzzy-PD controller employs proportional and derivative error signals as its inputs and produces the incremental control action as the output, resulting in smoother and more adaptive control behavior.

➤ *Define Input and Output Variables*

In the fuzzy-PD control design for the overhead crane system, two input variables and one output variable are defined to achieve accurate trolley positioning and swing suppression.

➤ *Controlled Plant*

The plant consists of the trolley–pendulum mechanism of the overhead crane. The control input is the horizontal driving force $u(t)$ applied to the trolley. The system outputs include the trolley displacement $x(t)$ and the payload swing angle $\theta(t)$, along with their time derivatives.

➤ *Fuzzy-PD Controller*

The controller generates the control increment $\Delta u(t)$based on the deviation of the trolley position from the reference trajectory.

- Inputs: Position error $e(t) = x_{\text{ref}}(t) - x(t)$and its rate of change $\Delta e(t) = \frac{de}{dt}$.
- Output: Incremental control signal $\Delta u(t)$, which is integrated to produce the final control action $u(t) = \int \Delta u(t)dt$.

This structure ensures a proportional–derivative behavior within a fuzzy inference framework, allowing adaptive control of both transient and steady-state responses.

➤ *Normalize Input and Output Variables*

For consistent fuzzy processing, all input and output signals are normalized to the range of $[-1,1]$within the fuzzy inference system. The normalization gains are defined as follows:

- Position error: $E = K_1 e$, with $K_1 = 10/8$.
- Error rate: $\dot{E} = K_2 \Delta e$, with $K_2 = 10/7$.
- Control increment: $\Delta U = K_3 \Delta u$, with $K_3 = 3$.

These scaling coefficients are selected based on the expected ranges of displacement, velocity, and control force, and can be fine-tuned to optimize the system's response.

➤ *Define Fuzzy Sets and Linguistic Terms*

Each input and output variable is represented by fuzzy sets with corresponding linguistic terms. The two input variables—error E and error rate $\dot{E}$ are described by five triangular membership functions: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB).

The output variable $\Delta U$is defined by seven triangular fuzzy sets: NB, Negative Medium (NM), NS, ZE, PS, Positive Medium (PM), and PB.The symmetric and overlapping triangular membership functions ensure smooth transitions between fuzzy regions, supporting continuous and stable control of the nonlinear crane system.

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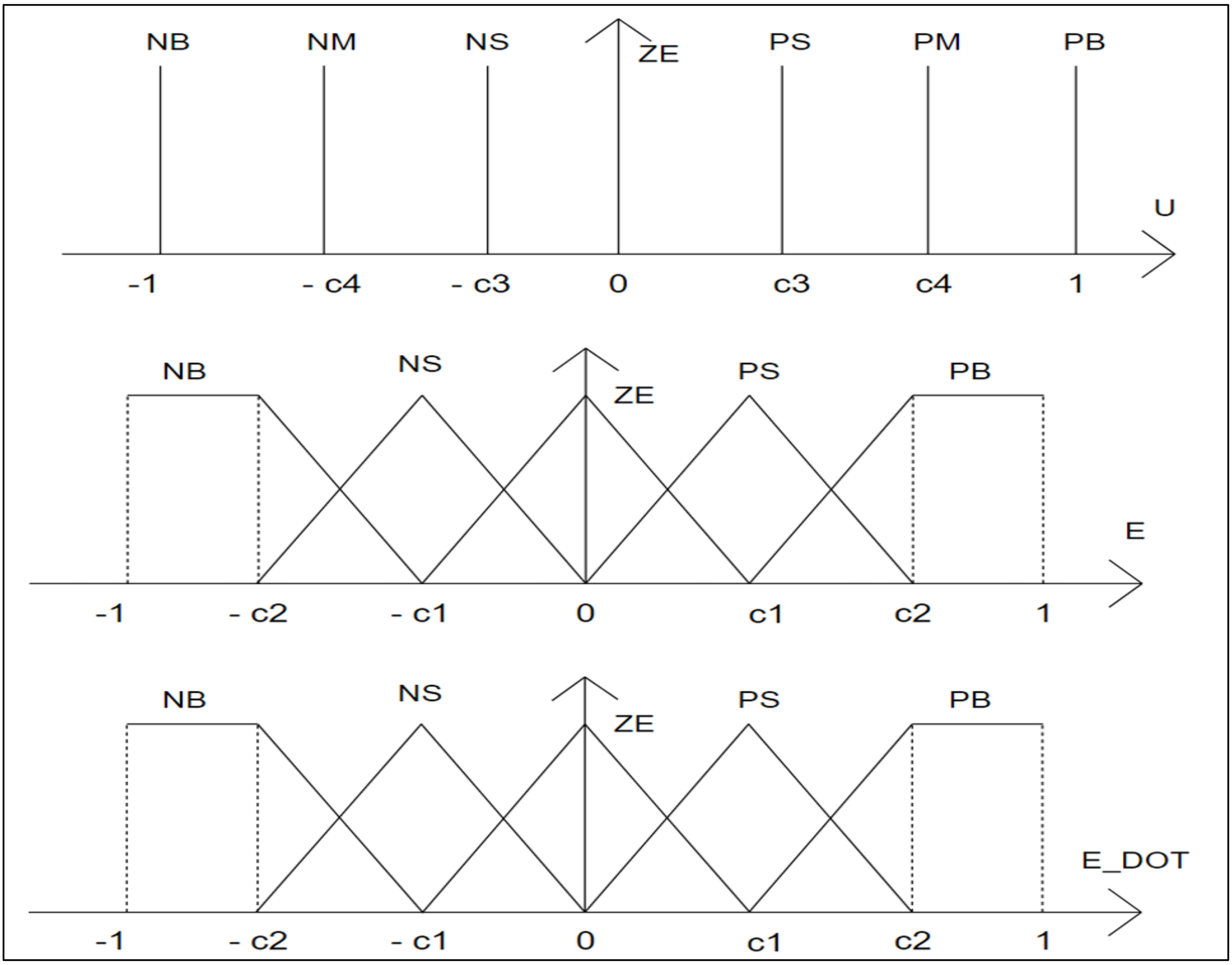
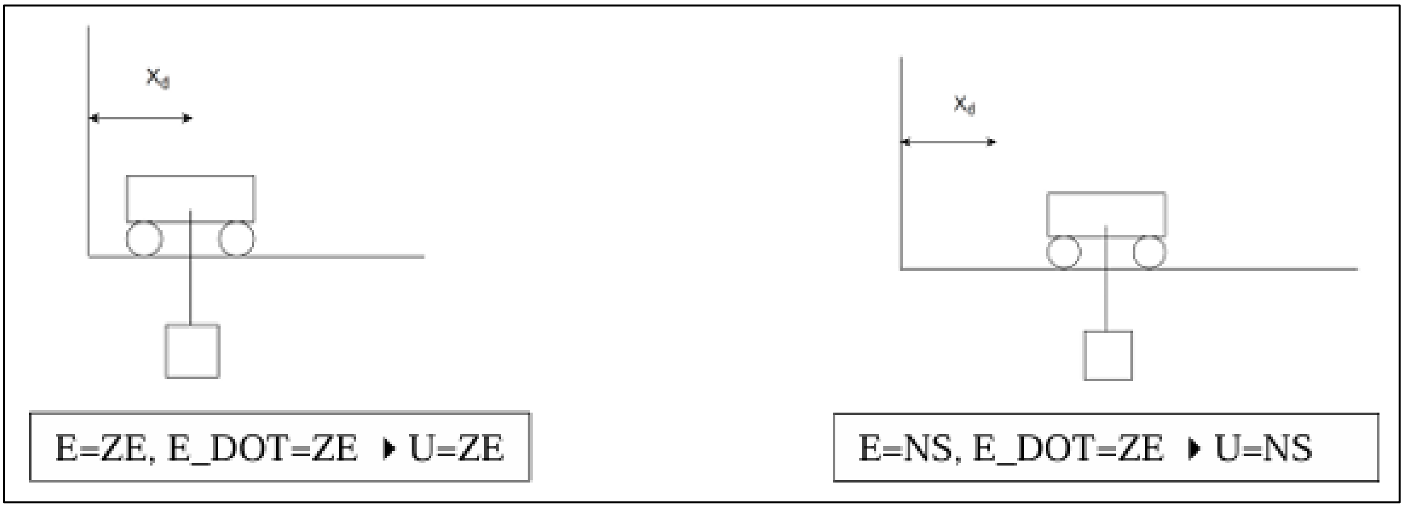


Fig 2 The Fuzzy Set of Controller

➢ *Formulate Fuzzy Rules*

Using expert knowledge and system response characteristics, a set of fuzzy inference rules is constructed to relate the input variables $(E, \dot{E})$ to the output variable ΔU. The rules are designed to emulate human decision-making in balancing the load oscillation and the trolley's motion. Examples of fuzzy rules are as figure follows:



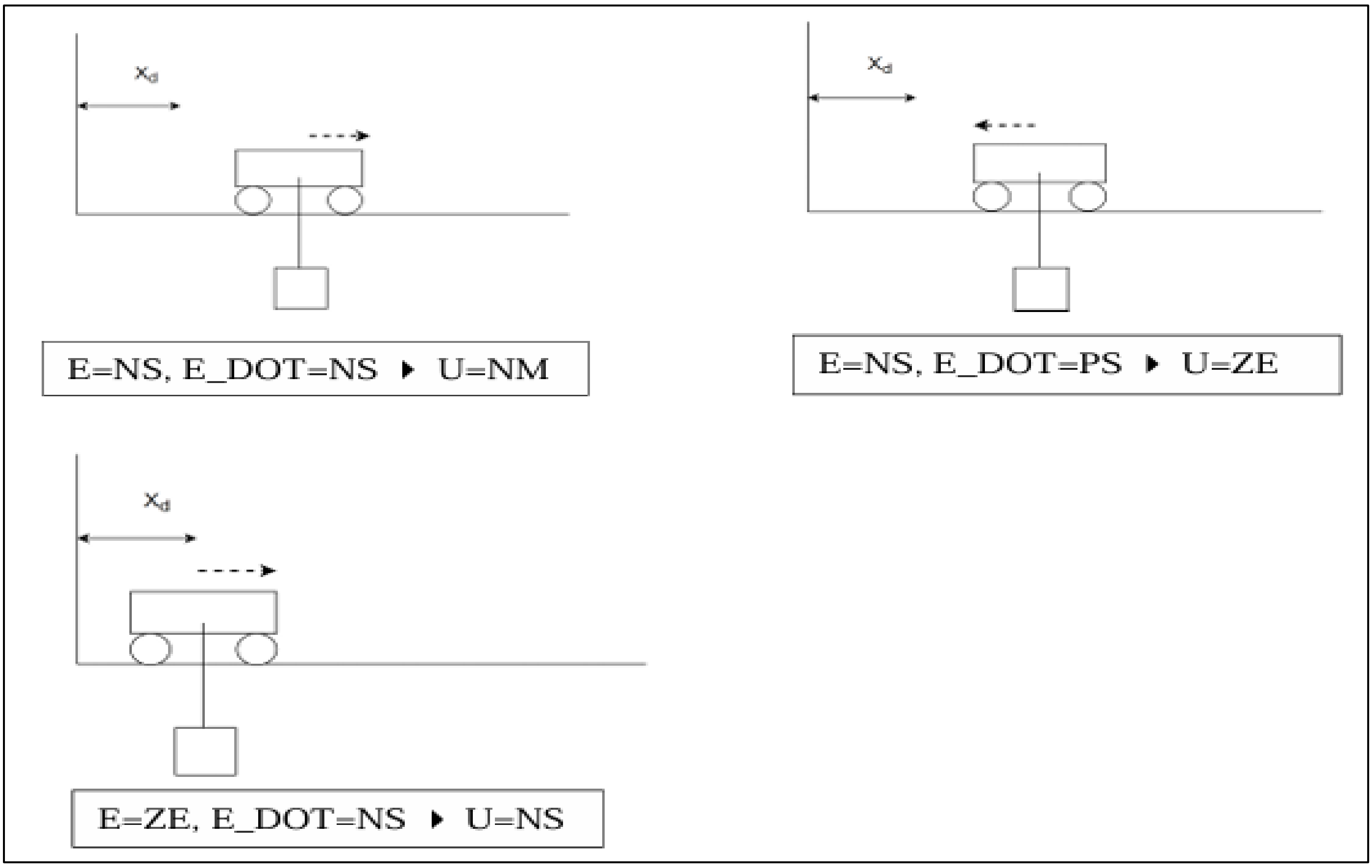


Fig 3 Illustration of Fuzzy Rules

The complete 5×5 fuzzy rule table in table 1 is constructed symmetrically to maintain uniform response across both positive and negative error domains. This structure provides a nonlinear mapping between the error dynamics and the required control effort, improving the controller's adaptability and robustness.

Table 1 Fuzzy Rule Table

U		***E***				
		NB	NS	ZE	PS	PB
$\dot{E}$	NB	NB	NB	NM	NS	ZE
	NS	NB	NM	NS	ZE	PS
	ZE	NM	NS	ZE	PS	PM
	PS	NS	ZE	PS	PM	PB
	PB	ZE	PS	PM	PB	PB

➢ *Select Inference and Defuzzification Methods*

The MAX–PROD inference method is adopted to compute the firing strength of each fuzzy rule as the product of the input membership degrees. The weighted average (centroid) defuzzification method is used to obtain the crisp output value ΔU, providing a continuous and stable control response. The resulting value is denormalized using the scaling factor $K_3$and integrated to generate the final control signal $u(t)$.

This fuzzy-PD approach combines the intuitive interpretability of fuzzy logic with the fast response characteristics of a PD controller. Simulation results confirm that the proposed fuzzy-PD controller yields improved position tracking accuracy, reduced overshoot, and effective suppression of payload swing compared with conventional PID and classical FLC strategies.

III. PROPOSED METHOD FOR SIMULATION USING MATLAB/SIMULINK

A comprehensive simulation study is conducted in MATLAB/Simulink to evaluate the performance of the proposed Fuzzy-PD control strategy applied to the overhead crane system. The objective is to verify the controller's ability to achieve accurate trolley positioning and effective swing suppression while maintaining fast and stable system responses. The simulation environment reproduces the nonlinear and underactuated dynamics of the overhead crane, integrates the fuzzy-PD control algorithm, and measures the system's behavior under various operating conditions and disturbances.

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➢ *System Modeling in Simulink*

The overhead crane system is modeled based on the nonlinear dynamic equations derived in the previous section, representing the coupled relationship between the trolley's translational motion and the pendulum-like swing of the suspended payload. The Simulink model consists of three main subsystems: (i) the crane dynamics, (ii) the fuzzy-PD controller block, and (iii) the feedback path connecting the plant outputs to the controller inputs.

➢ *Overhead Crane Dynamics*

The plant subsystem implements the differential equations governing the trolley displacement x and the payload swing angle θ. These equations capture the effects of gravity, payload mass, cable length, and the nonlinear coupling between horizontal motion and angular swing. The model operates in continuous time, ensuring accurate representation of the oscillatory behavior during acceleration and deceleration phases.

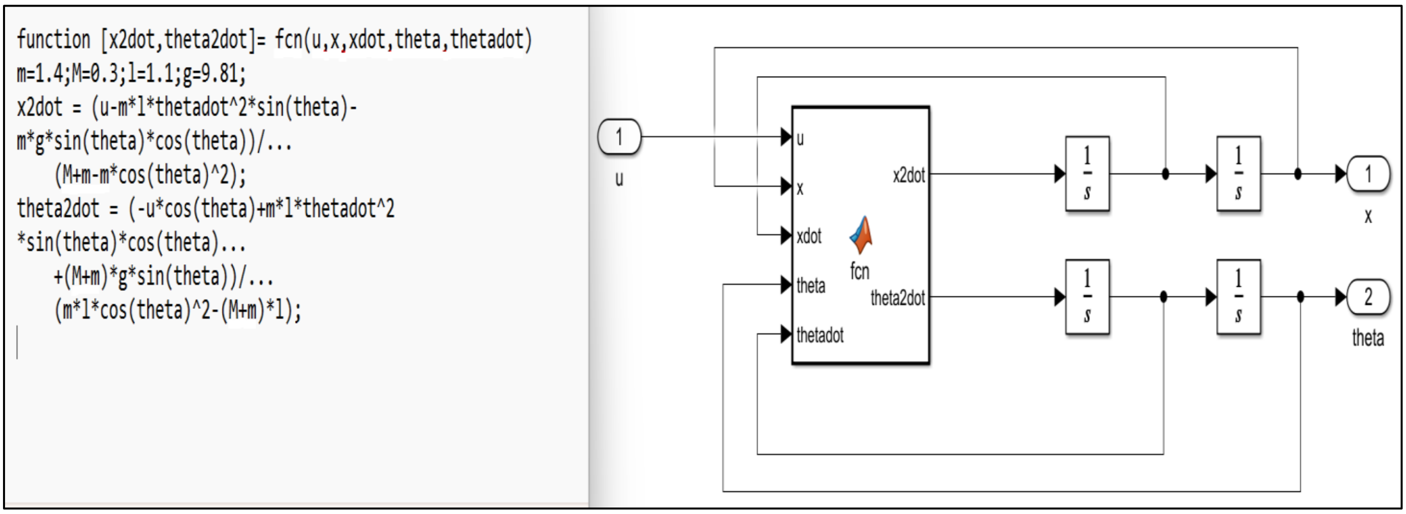

Fig 4 Simulink Model of Ball and Beam System

➢ *Control Force Generation*

The control input $u(t)$corresponds to the horizontal force applied to the trolley. The fuzzy-PD controller computes this force incrementally based on the position error $e(t) = x_{\text{ref}} - x(t)$and its rate of change $\dot{e}(t)$. The controller output $\Delta u(t)$is integrated to obtain the total control signal $u(t) = \int \Delta u(t)dt$, which drives the plant model. This configuration ensures smooth actuation and reduces noise sensitivity in comparison with classical derivative-based control.

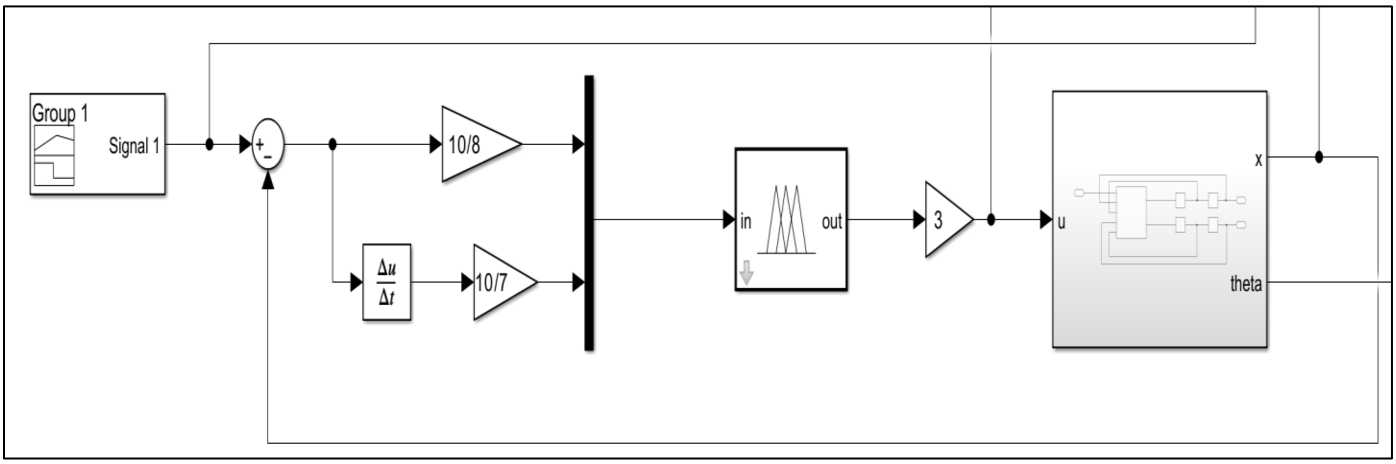

Fig 5 Fuzzy Logic Controller for Overhead Crane Dynamics

➢ *Nonlinearities and External Disturbances*

The model incorporates nonlinear terms involving trigonometric and centrifugal components, friction, and variable coupling effects between $x$and θ. To assess robustness, small random disturbances are applied to simulate external perturbations such as cable vibration and parameter uncertainties.

➢ *Fuzzy-PD Controller Schematic*

The Fuzzy-PD controller is implemented as an independent block that processes the normalized error and error-rate signals to generate the incremental control command. The Simulink implementation includes gain normalization, a fuzzy inference engine, and an integration stage for producing the physical actuation signal.

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➢ *Input and Output Normalization*

All input and output signals are normalized within the range $[-1,1]$ using the following scaling coefficients obtained from the simulation setup:

- Position error: $-0.8 \le e \le 0.8\text{m} \quad \rightarrow \quad K_1 = 10/8$
- Velocity (error rate): $-0.7 \le \dot{e} \le 0.7\text{m/s} \quad \rightarrow \quad K_2 = 10/7$
- Control force: $-3 \le u \le 3\text{N} \quad \rightarrow \quad K_3 = 3$

The normalized inputs $E = K_1 e$ and $\dot{E} = K_2 \dot{e}$ are sent to the fuzzy inference system (FIS), and the normalized output $\Delta U$is rescaled by K_3before integration.

➢ *Controller Structure*

The controller uses two input variables $(E, \dot{E})$ and one output variable (ΔU), each defined by triangular membership functions. The fuzzy inference process follows the MAX–PROD rule aggregation method, and the centroid (weighted-average) technique is used for defuzzification. The resulting incremental command Δu is integrated through a $1/s$ block to produce the actual control force $u(t)$applied to the crane.

➢ *Closed-Loop Feedback*

The trolley displacement $x(t)$is measured and compared with the reference position $x_{\text{ref}}$to compute the error $e(t)$, while the derivative $\dot{e}(t)$ is obtained through a rate-of-change block. Both signals are continuously fed back into the fuzzy-PD controller, forming a closed-loop control system that adapts in real time to maintain precise trolley motion and suppress payload oscillation.

IV. EXPERIMENTAL RESULT AND DISCUSSION

The performance of the proposed Fuzzy-PD controller for the overhead crane system was evaluated through MATLAB/Simulink simulations under multi-step reference commands in Figure 6. The control objective was to track the desired trolley position while minimizing the oscillation of the suspended payload. The reference trajectory (Signal Builder) applied to the system consisted of multiple position steps between 0.5 m and 2 m, designed to test the controller's adaptability and robustness during both acceleration and deceleration phases.

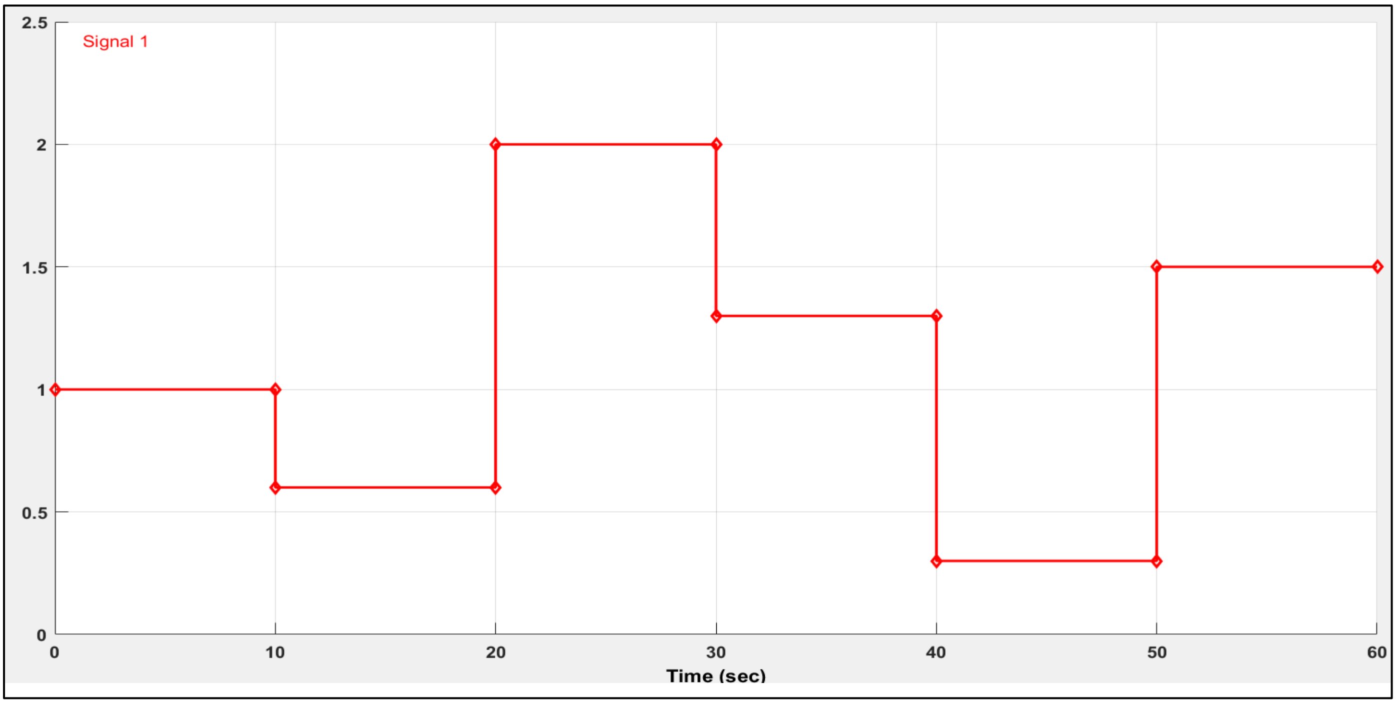

Fig 6 Input Signal for Overhead Crane System

➢ *Control Signal Response*

The control signal $u(t)$generated by the Fuzzy-PD controller, as shown in figure 6, exhibits an adaptive and well-damped behavior throughout the simulation period. Each time the reference position changes, the controller immediately produces a corrective action within the bounded force range (±3 N). The peaks in $u(t)$correspond to the initiation of trolley acceleration or braking, allowing the system to respond rapidly to step changes. After the transient phase, the control force decays smoothly toward zero, confirming the stability and energy efficiency of the control law. The absence of high-frequency oscillations in the control signal indicates that the integration stage of the Fuzzy-PD structure effectively suppresses noise amplification commonly observed in conventional PD controllers.

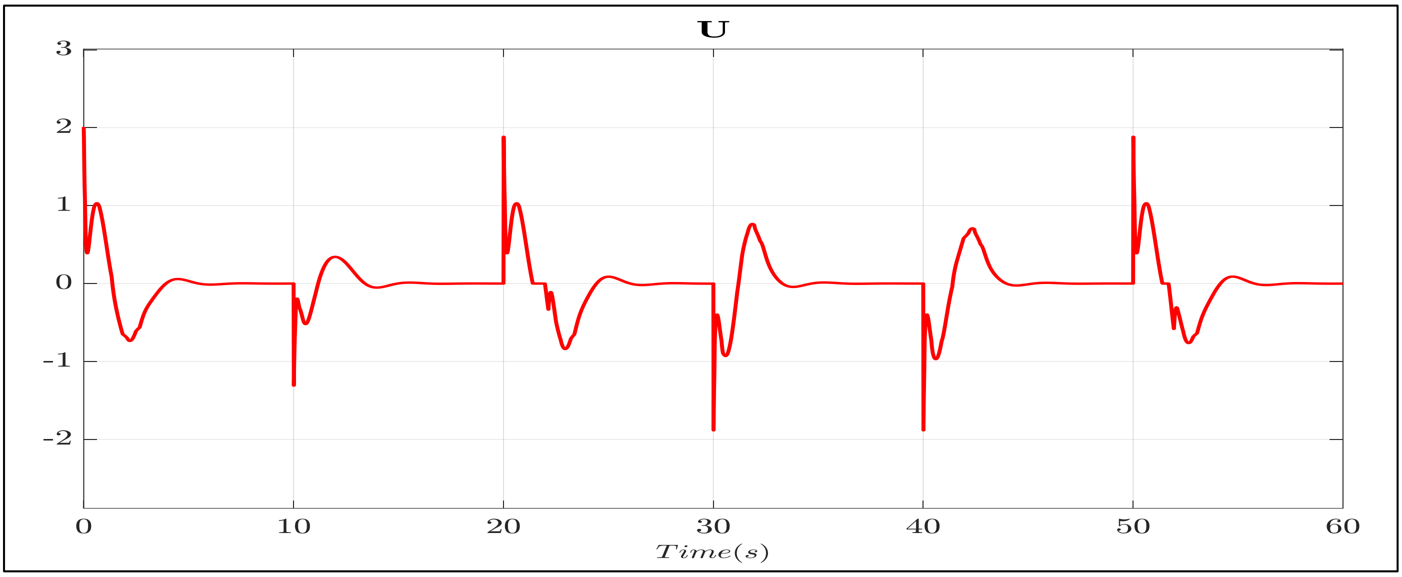

Fig 7 Control Signal for Overhead Crane System

➢ *Trolley Position Tracking*

Figure 8 illustrates the tracking performance of the trolley position $x(t)$with respect to the reference trajectory $x_d(t)$. The trolley motion closely follows the desired trajectory with minimal steady-state error. For each position change, the trolley reaches the target within approximately 3 seconds, demonstrating fast convergence and excellent transient performance. The motion remains smooth with no overshoot or oscillatory behavior, even during consecutive reference transitions. This confirms that the fuzzy inference mechanism adaptively adjusts the control effort based on both the magnitude and rate of error variation, resulting in an optimal balance between responsiveness and stability.

➢ *Payload Swing Angle*

Figure 8 presents the payload swing response, represented by the angular displacement $\theta(t)$. During each acceleration or deceleration phase, small oscillations occur due to inertial coupling between the trolley and payload; however, these oscillations are rapidly damped by the fuzzy-PD controller. The maximum swing amplitude remains below 0.1 rad (≈ 5.7°) and decays quickly to near zero after each position change. This demonstrates that the proposed control method effectively suppresses residual oscillations, ensuring smooth payload motion and preventing excessive sway that could compromise safety or positioning accuracy.

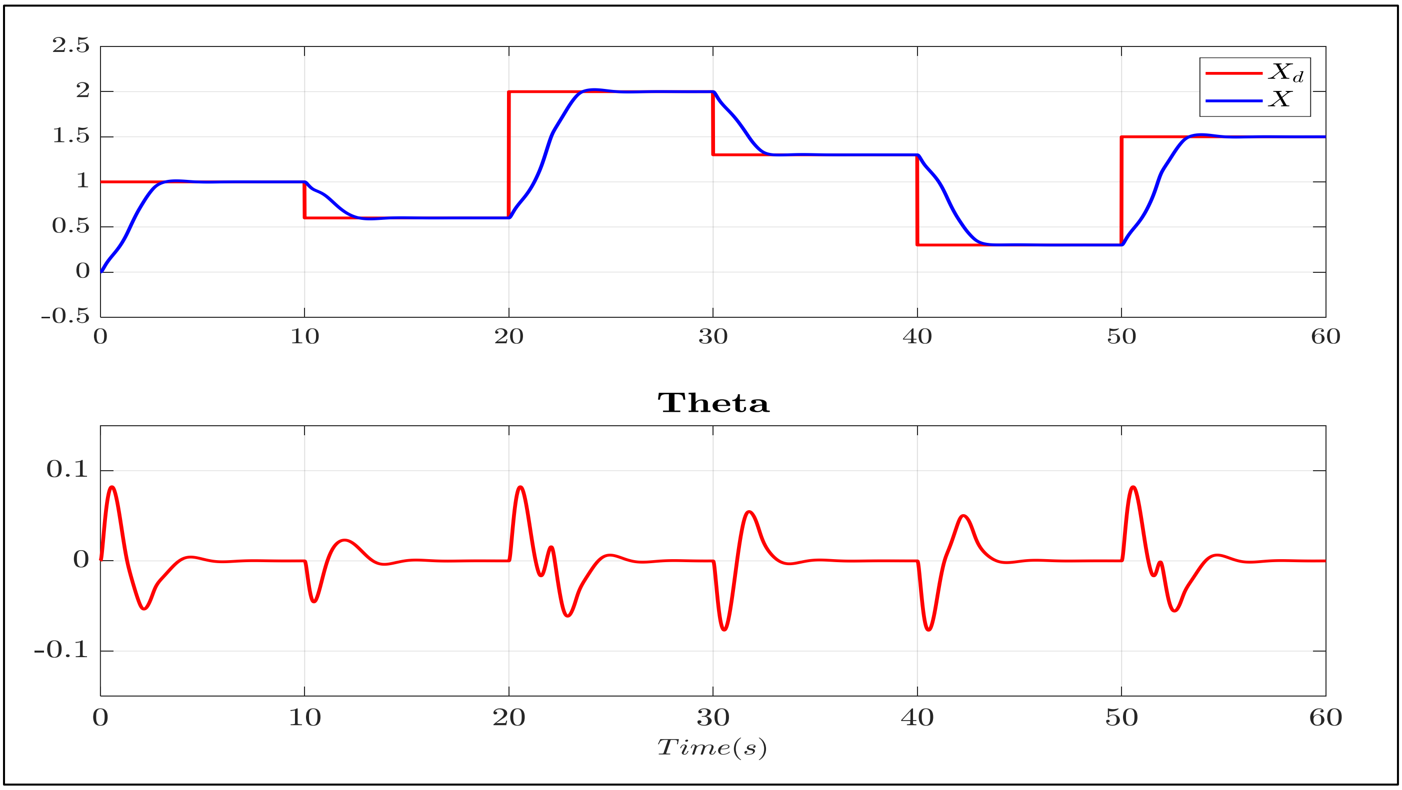

Fig 8 Respond Overhead Crane System

➢ *Overall System Performance*

The overall system exhibits short settling time, smooth control behavior, and minimal swing amplitude, validating the effectiveness of the proposed Fuzzy-PD approach for nonlinear and underactuated crane dynamics. Compared with traditional PID or classical fuzzy controllers, the fuzzy-PD design provides faster transient response, reduced overshoot, and improved damping characteristics, while maintaining a simple structure and interpretable rule base.

V. CONCLUSION

This paper presented the design and implementation of a Fuzzy-Proportional–Derivative (Fuzzy-PD) controller for the nonlinear and underactuated overhead crane system. The main objective was to achieve fast trolley positioning while minimizing payload swing, a challenging task due to the strong coupling between translational and pendulum-like rotational dynamics.

The proposed controller combines the adaptive reasoning capability of fuzzy logic with the fast response characteristics of a PD structure. By utilizing the position error and its rate of change as input variables, the Fuzzy-PD controller generates a smooth and adaptive control action that effectively compensates for nonlinear coupling and parameter variations. The normalization and denormalization scaling factors ensure stable fuzzy inference and consistent control effort across different operating conditions.

Simulation results obtained from MATLAB/Simulink demonstrate that the proposed control method provides significant improvements over conventional PID and classical fuzzy controllers. The trolley position accurately tracks the reference trajectory with a short settling time (approximately 3–5 seconds) and negligible steady-state error, while the payload swing angle remains below 0.1 rad. The control signal is smooth, bounded within ±3 N, and energy-efficient, confirming the controller’s ability to provide fast response without causing excessive actuation or oscillation.

Overall, the study confirms that the Fuzzy-PD controller is an effective and robust solution for controlling nonlinear overhead crane systems. It successfully achieves the dual objectives of rapid positioning and oscillation suppression while maintaining a simple, interpretable structure suitable for real-time implementation. Future research may focus on extending this approach by integrating optimization algorithms such as genetic or swarm intelligence techniques for automatic tuning of membership functions and rule bases, or by deploying the controller on a real-time embedded platform for experimental validation.

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