Adaptive fuzzy proportional integral derivative control for azimuth rotational positioning system

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ABSTRACT

This paper presents an adaptive fuzzy logic-based proportional–integral–derivative (PID) control strategy for an azimuth rotational positioning system characterized by nonlinear angular dynamics. Conventional fixed-gain PID controllers often experience performance degradation when operating across varying error regions, resulting in slower responses and residual steady-state errors. To address this limitation, a region-based fuzzy gain scheduling mechanism is proposed to dynamically adjust the proportional (Kp), integral (Ki), and derivative (Kd) gains according to the instantaneous angular error. The proposed controller is implemented on a laboratory-scale embedded platform consisting of a stepper motor actuator, potentiometer-based angular feedback, and an Arduino Nano controller. Experimental evaluations were conducted at reference angles of 45°, 90°, 135°, and 180° and compared with a conventional PID controller. Results demonstrate that the adaptive fuzzy–PID controller completely eliminates steady-state error at all tested setpoints and reduces rise time by up to 56.7%, depending on the operating condition. The adaptive gain adjustment enables faster transient response for large angular deviations while maintaining stable convergence near the setpoint. These findings demonstrate that the proposed embedded region-based adaptive fuzzy–PID approach provides an effective and practical solution for improving positioning accuracy and dynamic performance in rotational positioning systems.

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1. INTRODUCTION

Precision rotational positioning systems are widely employed in industrial automation, robotic mechanisms, antenna steering devices, and intelligent mechatronic platforms [1]–[4]. Accurate angular positioning is essential to ensure stable and responsive system performance. However, nonlinear dynamics, actuator limitations, friction effects, and varying load characteristics often degrade control accuracy and transient response in practical rotational systems [4]–[7]. Accurate azimuth and elevation positioning is particularly critical in applications such as localization frameworks, geodetic alignment, solar tracking platforms, inertial navigation systems (INS), antenna pointing mechanisms, and spacecraft orientation control. Previous studies have demonstrated that coordinate system rotation and azimuth–elevation measurement configurations significantly influence estimation and positioning accuracy [8], [9]. In solar tracking systems, precise azimuth control directly affects energy harvesting efficiency under continuously varying environmental conditions [10], [11]. These applications highlight a common requirement: reliable and robust azimuth rotational control capable of maintaining precision under dynamic reference variations.

To improve rotational positioning performance, various advanced control strategies have been investigated. Tracking differentiator-based fuzzy logic-based proportional–integral–derivative (PID) control has been applied to single-axis INS to enhance robustness against disturbances and eliminate steady-state error [12]. In antenna pointing systems, fuzzy–PID controllers have demonstrated improved settling time, reduced overshoot, and enhanced pointing accuracy compared to conventional PID control [13]. Similarly, optimized fuzzy–PID approaches have been employed for spacecraft docking maneuvers to address nonlinear orientation dynamics and reduce tracking error under uncertain operating conditions [14]. Despite these advancements, most existing implementations focus on aerospace or navigation applications, while experimental validation on microcontroller-based azimuth rotational positioning platforms with region-based adaptive gain scheduling remains limited.

The PID controller remains one of the most widely used control strategies due to its simple structure and ease of implementation [15], [16]. Although satisfactory for many linear systems, fixed-gain PID controllers often experience performance degradation under nonlinear conditions and wide error variations. Large angular deviations generally require aggressive gains for rapid convergence, whereas near-setpoint operation demands smoother control action to prevent overshoot and oscillations. Consequently, conventional tuning methods such as Ziegler–Nichols may not always provide optimal performance under varying operating conditions [17].

To overcome these limitations, adaptive and intelligent control approaches have been increasingly adopted. Fuzzy logic provides an effective framework for handling nonlinear and uncertain systems without requiring an exact mathematical model. By combining fuzzy inference with PID control, controller gains can be adjusted according to operating conditions, enabling improved adaptability and transient performance. Previous studies have reported the effectiveness of fuzzy-based PID tuning in various nonlinear motion systems [18]–[20]. Although previous studies have demonstrated the effectiveness of fuzzy–PID controllers in aerospace, navigation, and robotic applications, several limitations remain. Most reported implementations focus on simulation studies or high-end control platforms, while experimental validation on low-cost embedded azimuth rotational positioning systems is still limited. Furthermore, existing studies generally employ fixed fuzzy rule structures without explicitly addressing region-based gain adaptation across different angular error conditions. As a result, the controller may not provide optimal responsiveness for both large angular displacements and near-setpoint operation.

Despite these advances, experimental validation of adaptive fuzzy–PID controllers on low-cost embedded azimuth rotational positioning platforms remains limited, particularly for region-based gain adaptation mechanisms under multiple angular setpoints [21]–[25]. To address this gap, this study proposes a region-based adaptive fuzzy–PID controller implemented on a microcontroller-based azimuth positioning system. The proposed approach dynamically adjusts PID gains according to instantaneous angular error, enabling faster transient response for large deviations while maintaining stable convergence near the setpoint.

The main contributions of this study are the development of a region-based adaptive fuzzy gain scheduling mechanism, implementation on a low-cost embedded microcontroller platform, experimental validation under multiple angular setpoints, and analysis of adaptive gain behavior on transient response improvement and steady-state error elimination.

2. METHOD

2.1. Research design

This study develops an azimuth rotational positioning system using an adaptive fuzzy–PID control strategy. The system is designed to align the rotational platform with a desired angular reference. The overall control structure consists of error calculation, fuzzy-based gain adaptation, and PID control. The angular error (Δ) is defined as the difference between the reference angle and the actual platform angle, as illustrated in Figure 1:

$$\Delta = \theta_1 - \theta_2$$

where θ_1 is the reference angle and θ_2 is the actual platform angle measured from a predefined positive x-axis. The calculated delta error serves as the input for the fuzzy-based adaptive gain tuning mechanism.

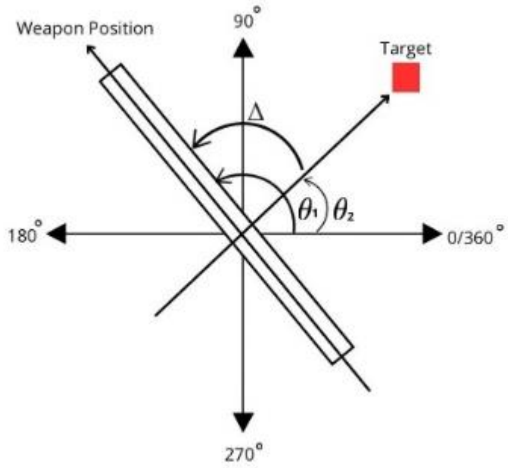


Figure 1. The illustration of delta error angle

2.2. System architecture

Figure 2 presents the block diagram of the proposed system. The delta error is processed through the fuzzy logic controller (FLC) to generate adaptive PID gains (K_p, K_i, K_d). These gains are applied to the PID controller, which generates the control signal for the stepper motor. The potentiometer provides real-time angular feedback, forming a closed-loop control system. Figure 3 illustrates the electrical schematic (Figure 3(a)) and three-dimensional (3D) mechanical design (Figure 3(b)) of the proposed azimuth rotational positioning system. A stepper motor is employed as the rotational actuator, while a multiturn potentiometer provides angular feedback for closed-loop control.

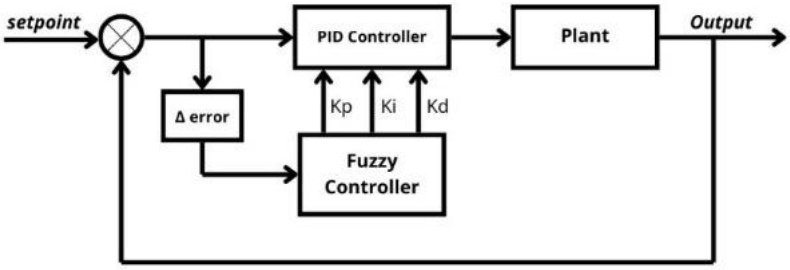
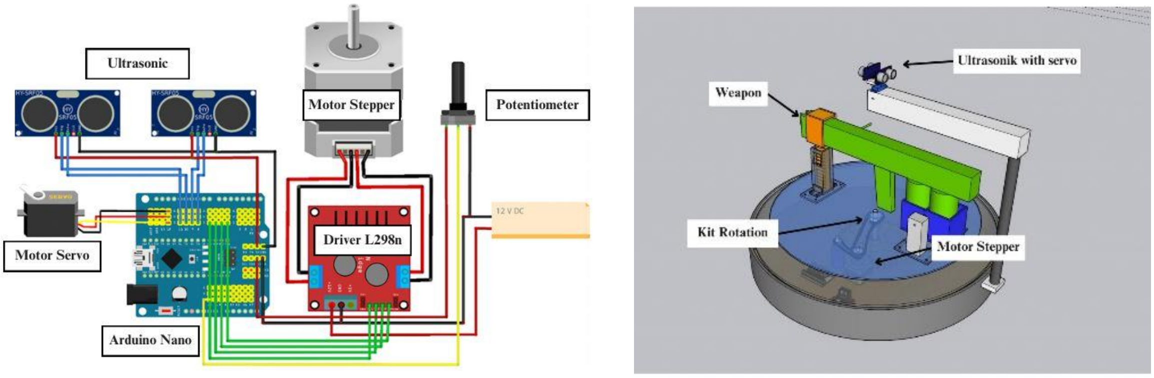


Figure 2. Block diagram system



(a) (b)

Figure 3. Design proposed system: (a) schematic design and (b) 3D design

2.3. FLC design

The FLC is designed to provide adaptive gain tuning for the PID controller based on the magnitude of the angular error. Unlike conventional fixed-gain PID control, the proposed FLC dynamically adjusts controller parameters according to the operating region of the system. This approach allows the controller to respond aggressively under large error conditions while maintaining stability and smooth response near the setpoint. The input variable of the fuzzy controller is the delta error (Δ), defined in (1). The delta error is classified into five linguistic variables: far negative (FN), close negative (CN), zero (Z), close positive (CP), and far positive (FP). The membership functions are defined over the range of −180° to 180°, corresponding to the full azimuth rotation capability of the system. Triangular and trapezoidal membership functions are employed to ensure smooth transitions between adjacent regions, as shown in Figure 4.

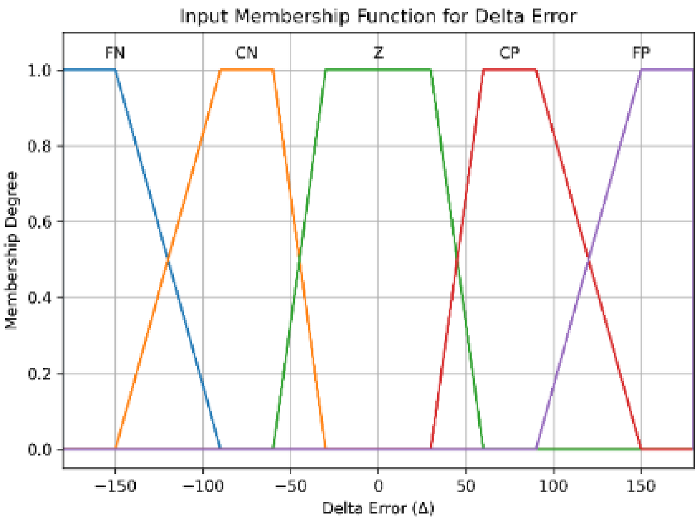


Figure 4. Membership input function

2.4. Fuzzy rule-based design

The fuzzy rule base consists of five IF–THEN rules, as presented in Table 1. The rule structure is designed based on control intuition and system behavior analysis. When the angular error is large (FN or FP), the proportional gain (K_p) is set to high in order to accelerate convergence. The derivative gain (K_d) is also increased to reduce oscillatory behavior during rapid correction. Meanwhile, the integral gain (K_i) is reduced to prevent excessive accumulation of error during large transients. When the error approaches zero (Z region), a lower proportional gain is applied to avoid overshoot, while a higher integral gain is used to eliminate steady-state error. The derivative gain is set to small to minimize sensitivity to noise. This rule configuration allows adaptive gain scheduling behavior without requiring an explicit mathematical model of the plant.

Table 1. Fuzzy rules for Kp, Ki, and Kd values

Rules	Input (delta error)	Output Kp	Output Ki	Output Kd
R1	FN	High	Less	Big
R2	CN	Middle	Regular	Normal
R3	Z	Low	Much	Small
R4	CP	Middle	Regular	Normal
R5	FP	High	Less	Big

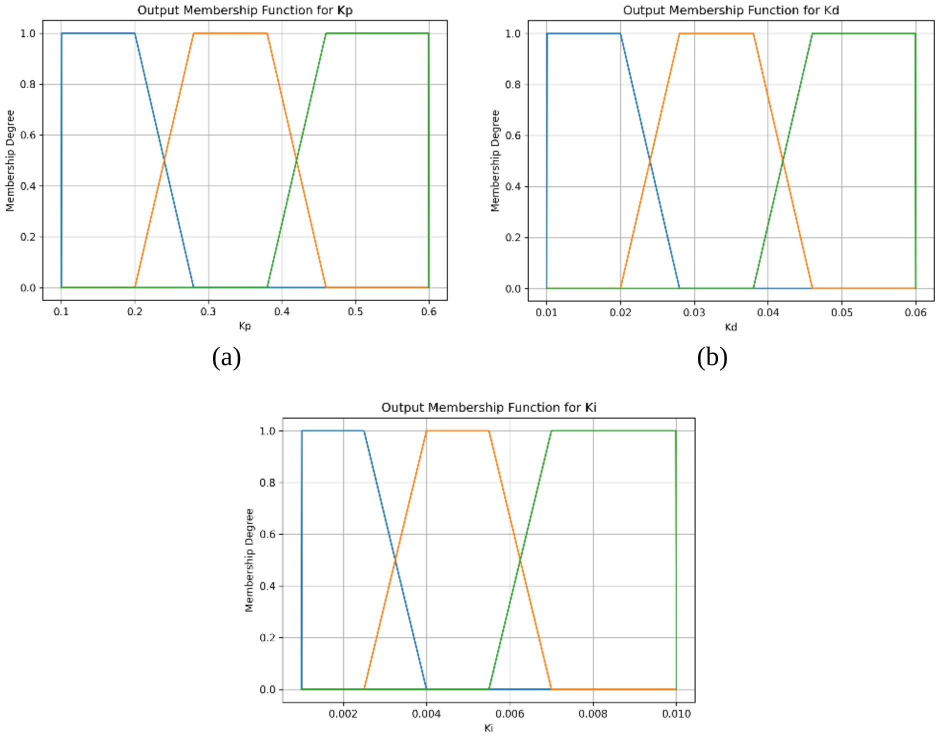
2.5. Output membership function

The output membership functions for the adaptive PID gains are shown in Figure 4 and defined within experimentally determined numerical ranges. The proportional gain K_p is categorized into three linguistic variables: low, middle, and high. The membership ranges are defined as follows: low: [0.10, 0.10, 0.20, 0.28]; middle: [0.20, 0.28, 0.38, 0.46]; and high: [0.38, 0.46, 0.60, 0.60]. Similarly, the integral gain K_i is divided into less, regular, and much with the following ranges: less: [0.001, 0.001, 0.0025, 0.004]; regular: [0.0025, 0.004, 0.0055, 0.007]; and much: [0.0055, 0.007, 0.010, 0.010]. The derivative gain K_d is categorized into small, normal, and big with membership ranges: small: [0.010, 0.010, 0.020, 0.028]; normal: [0.020, 0.028, 0.038, 0.046]; and big: [0.038, 0.046, 0.060, 0.060]. These numerical ranges were determined experimentally to ensure stable system behavior and adequate transient response. By defining overlapping membership regions, smooth transitions between gain levels are achieved, preventing abrupt changes in controller output.

2.6. Defuzzification mechanis

Figures 5(a) to (c) presents the output membership functions used to generate adaptive PID gains (Kp, Ki, and Kd). The overlapping membership regions enable smooth gain transitions and prevent abrupt parameter changes during operation. The Mamdani inference method is applied due to its intuitive rule representation and suitability for nonlinear control systems. The centroid method is used for defuzzification to obtain crisp output values for K_p, K_i, K_d. The centroid computation is expressed as $Z^* = \frac{\int \mu_x(z) z\, dz}{\int \mu_x(z) dz}$, where Z^* represents the defuzzified output value.

The resulting adaptive PID gains are updated in real time and applied directly to the PID controller, forming a hybrid fuzzy–PID control scheme. The proposed fuzzy inference structure employs a single-input variable and a compact rule base consisting of five rules, resulting in low computational complexity and efficient memory utilization. This simplified architecture was intentionally selected to facilitate real-time implementation on resource-constrained embedded hardware while maintaining satisfactory control performance.



(a) (b) (c)

Figure 5. Membership output function: (a) proportional gain (Kp) membership function, (b) integral gain (Ki) membership function, and (c) derivative gain (Kd) membership function

3. RESULTS AND DISCUSSION

3.1. Experimental results

The mechanical configuration of the proposed azimuth rotational positioning system is shown in Figure 6. The system integrates a stepper motor-driven rotational platform, an ultrasonic–servo subsystem for reference detection, and a potentiometer for angular feedback. The ultrasonic sensor performs full 360°

scanning to determine the reference direction, which is then processed as the angular setpoint. System performance was evaluated at reference angles of 45°, 90°, 135°, and 180°. Figures 7 to 10 illustrate the angular responses of the conventional PID and adaptive fuzzy–PID controllers. The quantitative comparison is summarized in Table 2.

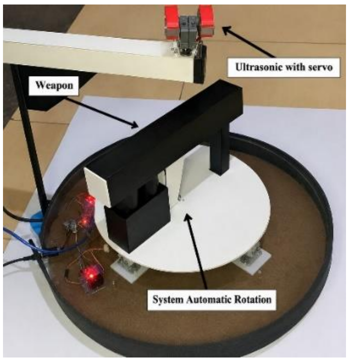


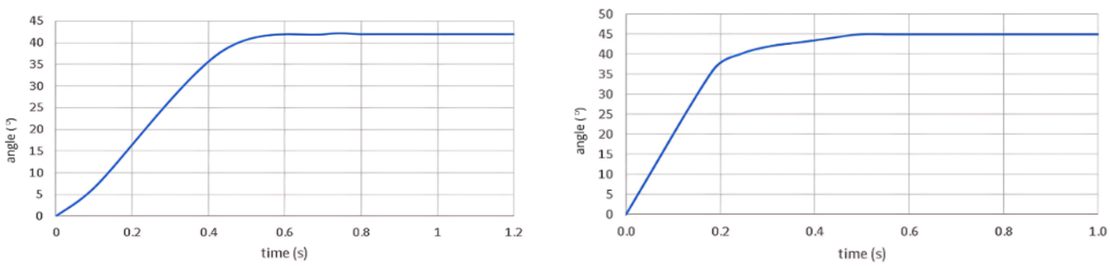
Figure 6. Mechanical construction

Table 2. Resume of testing results

Setpoint	Steady state error (%)		Rise time (second)	
	PID	Fuzzy-PID	PID	Fuzzy-PID
45	6.7	0.0	0.406	0.215
90	4.4	0.0	0.649	0.281
135	4.4	0.0	0.914	0.504
180	2.2	0.0	1.140	1.052

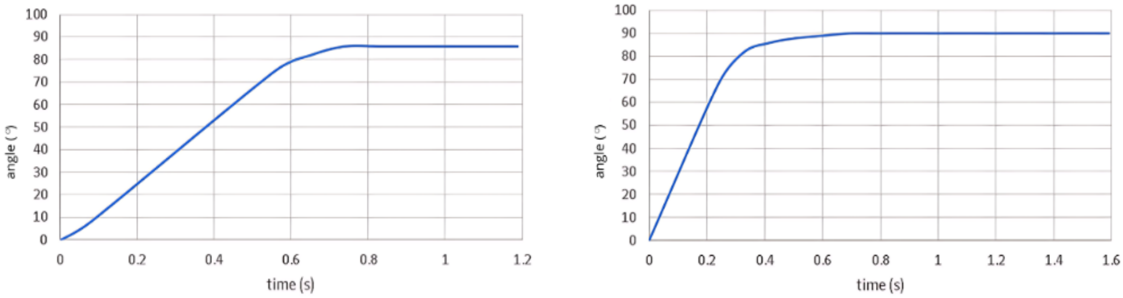
The improvement achieved by the proposed controller varies according to the reference angle. For small and medium angular displacements (45°–135°), the adaptive fuzzy–PID controller provides substantial reductions in rise time, ranging from 44.9% to 56.7%. This behavior indicates that the adaptive gain mechanism effectively increases controller aggressiveness when larger tracking errors are detected while gradually reducing the gains as the system approaches the desired position. Consequently, faster convergence can be achieved without introducing excessive oscillations. For the 45° setpoint, the adaptive fuzzy–PID reduced rise time from 0.406 s to 0.215 s (47.0% improvement) while eliminating steady-state error. At 90°, the rise time improved by approximately 56.7%. For 135°, improvement reached 44.9%. At 180°, the improvement was smaller (7.7%), although steady-state error was completely removed in all cases. These results demonstrate that the adaptive fuzzy–PID controller consistently improves transient response and positioning accuracy compared to the conventional fixed-gain PID controller.

The dynamic responses of the conventional PID controller and the proposed adaptive fuzzy–PID controller were evaluated under four reference angles, namely 45°, 90°, 135°, and 180°. For each test, the angular response was recorded and analyzed in terms of rise time, steady-state error, and transient characteristics. Figures 7(a) to 10(a) present the responses obtained using the conventional PID controller, while Figures 7(b) to 10(b) show the responses achieved using the proposed adaptive fuzzy–PID controller.



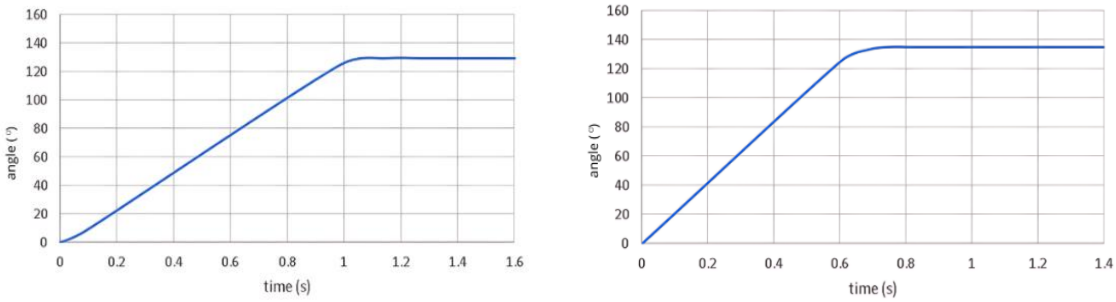
(a) (b)

Figure 7. System response using setpoint value of 45°: (a) PID and (b) fuzzy-PID



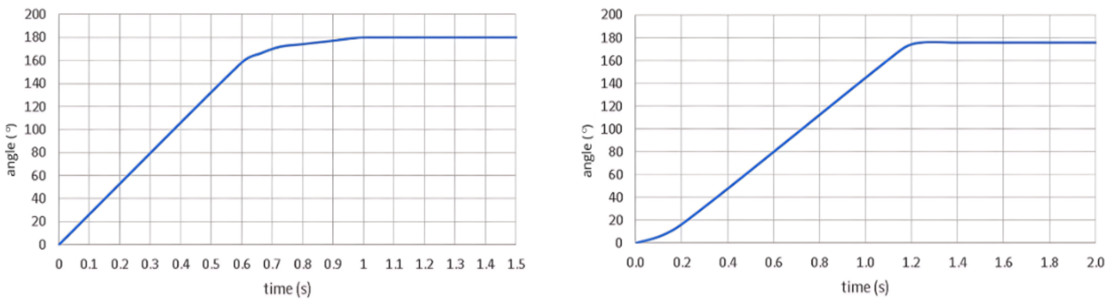
(a) (b)

Figure 8. System response using setpoint value of 90°: (a) PID and (b) fuzzy-PID



(a) (b)

Figure 9. System response using setpoint value of 135°: (a) PID and (b) fuzzy-PID



(a) (b)

Figure 10. System response using setpoint value of 180°: (a) PID and (b) fuzzy-PID

For the 180° setpoint, the rise-time improvement is comparatively smaller, reaching approximately 7.7%. This phenomenon is primarily associated with the mechanical characteristics of the experimental platform. At larger angular displacements, the stepper motor must sustain corrective action over a longer travel distance, making the influence of rotational inertia, friction, and available motor torque more significant. Under these conditions, the mechanical limitations of the actuator become dominant factors that restrict further acceleration, thereby reducing the relative benefit of adaptive gain adjustment.

3.2. Adaptive gain behavior and computational validation

The performance improvement achieved by the proposed controller is primarily attributed to region-based gain adaptation. When the angular error is large, higher proportional and derivative gains are assigned to accelerate corrective action, whereas near the setpoint the proportional and derivative gains are reduced while the integral gain is increased to eliminate residual steady-state error. This adaptive gain scheduling mechanism enables faster convergence while maintaining stability and reducing oscillation risk. For a representative delta error of 45°, the embedded controller generated gains of $K_p = 0.3116, K_i = 0.0054$, and $K_d = 0.0312$, which closely matched the manually calculated centroid values of $K_p = 0.312, K_i = 0.0056$, and $K_d = 0.0312$. The negligible difference confirms the correct implementation of the fuzzy inference and defuzzification processes on the microcontroller platform.

3.3. Comparison with conventional PID and mechanical limitations

Initial PID tuning using the Ziegler–Nichols method produced aggressive gains ($K_p = 1.25$, $K_i = 0.05$, and $K_d = 0.038$) and unsatisfactory transient behavior. Although retuning improved performance ($K_p = 0.5, K_i = 0.008$, and $K_d = 0.005$), fixed gains remained unable to accommodate varying operating conditions. In contrast, the proposed adaptive fuzzy–PID controller dynamically adjusted gains according to angular error, resulting in improved transient response and zero steady-state error across all tested setpoints. The smaller improvement observed at the 180° setpoint was primarily attributed to mechanical inertia and motor torque limitations. Overall, the results demonstrate the effectiveness of the proposed controller in enhancing positioning accuracy and transient performance; however, validation was limited to nominal step-response tests, and future work will focus on disturbance rejection, load variation, and dynamic trajectory-tracking scenarios.

4. CONCLUSION

This study proposed a region-based adaptive fuzzy–PID controller for azimuth rotational positioning systems. Experimental results demonstrated complete elimination of steady-state error and rise-time improvements of up to 56.7% compared with conventional PID control. The adaptive gain scheduling mechanism enabled faster transient response while maintaining stable convergence near the setpoint. Although validation was limited to step-response testing under nominal conditions, the results confirm the effectiveness of the proposed approach for embedded rotational positioning applications. Future work will focus on disturbance rejection, robustness evaluation, and implementation in more complex rotational systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mufid Ridlo Efendi	✓		✓	✓			✓			✓	✓		✓	
Rina Mardiati	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	
Muhammad Bagja Nasrulloh			✓			✓	✓	✓	✓					
Aan Eko Setiawan		✓			✓				✓					

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study, request.

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