Design of an adaptive fuzzy–PID controller for a DC motor-based railway barrier system

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ABSTRACT

Railway level crossings require reliable barrier systems to operate safely under changing conditions. In practice, DC motor–driven barriers are influenced by load variations, disturbances, and nonlinear behavior, which can limit the performance of conventional PID control. In this study, an adaptive fuzzy–PID controller is developed, where fuzzy logic adjusts the PID parameters online based on the control error and its rate of change. The system is modeled and tested in MATLAB/Simulink, and then implemented on an STM32 microcontroller for real-time validation. The results show that the proposed controller reduces overshoot from 12.76% to 0.85% and provides a smoother response under load disturbances. A slightly longer settling time is observed, but the system remains stable and well-damped during operation. Experimental tests also show consistent behavior, suggesting that the approach can be applied in practical railway barrier systems.

Keywords: Fuzzy–PID control; Adaptive control; DC motor; Automatic railway barrier system; STM32.

1. INTRODUCTION

Railway level crossings are critical components of railway transportation systems, where safety depends on the reliable operation of automatic barrier mechanisms. Numerous accidents at these locations highlight the need for fully automated systems to reduce human error and improve traffic safety [1, 2]. DC motors are widely used in such applications due to their fast dynamic response and ease of integration with embedded platforms [3-6]. In practical operation, DC motor–driven barrier systems are exposed to significant load variations caused by wind, gravity, friction, and mechanical wear. These factors introduce nonlinearities and parameter uncertainties into the dynamics, which degrade the performance of conventional PID control with fixed gains [7, 8]. As a result, excessive overshoot, long settling time, and steady-state errors may occur under disturbances, making classical PID control unsuitable for safety-critical applications.

Fuzzy logic control has proven effective for nonlinear and uncertain systems without requiring precise mathematical models [9]. By integrating fuzzy logic with PID control, adaptive fuzzy–PID controllers can adjust control parameters online according to the control error and its rate of change, thereby improving robustness and transient performance [10]. Previous studies have shown that this approach outperforms conventional PID methods in motor drive applications under varying load conditions [11, 12]. However, most existing studies primarily focus on general-purpose DC motor drives or laboratory-scale experiments, while limited attention has been given to automatic railway barrier systems characterized by application-specific load variations and strict real-time implementation requirements. Furthermore, practical deployment on low-cost embedded platforms remains insufficiently addressed in the current literature [10].

To overcome these limitations, this paper presents the design and implementation of an adaptive fuzzy–PID approach for an automatic railway barrier system driven by a DC motor. A dynamic model incorporating load torque variations and nonlinear characteristics is developed and an adaptive fuzzy–PID controller is designed based on established online parameter tuning principles. The proposed control structure is optimized for real-time implementation on an STM32 microcontroller [13], while monitoring and data acquisition are achieved using an ESP32-based architecture [14]. Controller performance is tested in MATLAB/Simulink under different load conditions and then compared with a conventional PID controller. After that, the method is also verified on a hardware prototype to check how it works in practice.

2. SYSTEM MODELING AND CONTROL DESIGN

2.1. System description and DC motor model

The automatic railway barrier system considered in this study is driven by a DC motor through a mechanical transmission mechanism to raise and lower the barrier arm. The main control objective is to ensure accurate and stable position tracking under varying operating conditions, particularly in the presence of load disturbances. The overall system architecture is illustrated in Figure 1, while the experimental setup is shown in Figure 2. The setup consists of a DC motor coupled with a mechanical load, and the control algorithm is implemented on an embedded hardware platform.

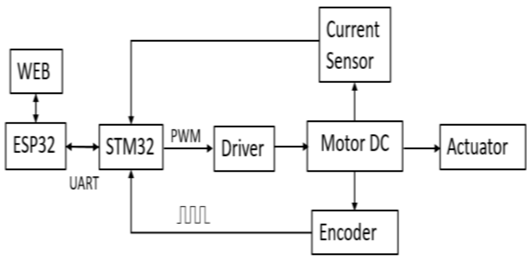


Figure 1. *Overview of the system.*

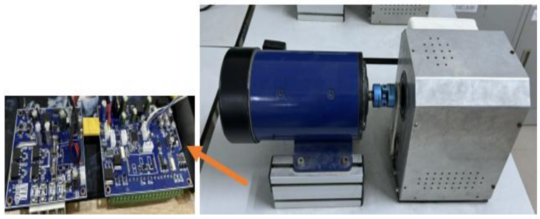


Figure 2. *Hardware setup for the experiment.*

In this setup, the control algorithm runs in real time on an STM32 microcontroller, where sensor data are collected and the fuzzy–PID control along with PWM signals are generated. An ESP32 module is used to send data and support remote monitoring through a web interface. During operation, variables such as motor position, control signals, and tracking error are transmitted to the web platform for visualization. The actuator is chosen for its simple structure and its suitability for position control, and its main parameters are given in Table 1.

Table 1. *DC motor model parameters.*

Symbol	Description	Value
U_n	Rated voltage	24 V
P_n	Rated power	500 W
n_n	Rated speed	2500 rpm
ω_n	Rated angular speed	261.8 rad/s
T_n	Rated torque	1.91 N·m
R_a	Armature resistance	0.21 Ω
L_a	Armature inductance	0.5 mH
K_e	Back electromotive force constant	0.091 V·s/rad
K_t	Torque constant	0.091 N·m/A
J	Rotor moment of inertia	1.2×10^{-4} kg·m²
B	Viscous friction coefficient	1.0×10^{-4} N·m·s/rad

The armature circuit dynamics are modeled as follows [5]:

$$R_a.i_a(t) + L_a.\frac{d\,i_a(t)}{dt} + K_e.\omega(t) = V_a(t) \quad (1)$$

The mechanical dynamics of the motor are given by:

$$J.\frac{d\omega(t)}{dt} + B.\omega(t) = K_t.i_a(t) - T_L(t) \quad (2)$$

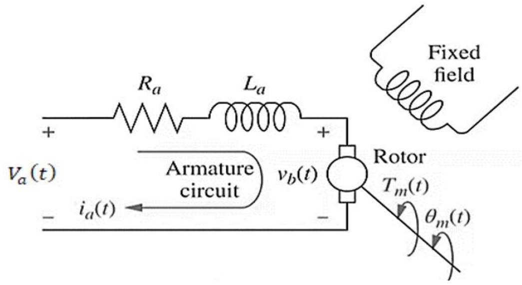


Figure 3. *DC motor model.*

The angular position of the motor shaft can be written as:

$$\frac{d\theta(t)}{dt} = \omega(t) \quad (3)$$

In real operating conditions, the railway barrier system is influenced by wind, vibration from passing trains, and gradual mechanical wear. These effects lead to variations in the load torque acting on the motor and introduce uncertainties in the system parameters. The load torque can be represented as follows:

$$T_L(t) = T_0 + \Delta T(t) \quad (4)$$

These uncertainties significantly degrade the performance of fixed-gain PID control, thus requiring an adaptive control strategy such as a fuzzy–PID controller. These equations form the basis for the subsequent controller design and simulation analysis.

2.2. Adaptive fuzzy–PID controller design

The proposed controller combines a conventional PID controller with a fuzzy inference system to adaptively tune the PID gains in real time. The fuzzy inference structure and rule base are designed based on common approaches reported in the literature [7, 16, 17].

In the time domain, the PID control law is expressed as follows, and its control principle is illustrated in the block diagram shown in Figure 4.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (5)$$

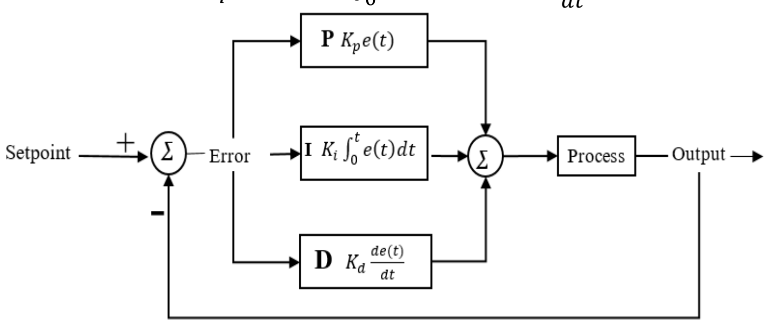


Figure 4. *Block diagram of the PID controller.*

To determine the controller parameters $\{K_p, K_i, K_d\}$, the Ziegler–Nichols experimental tuning method [15] is employed for the motor position control model. The adaptive fuzzy–PID control law is expressed as follows [7]:

$$u(t) = K_p(t).e(t) + K_i(t).\int_0^t e(t)dt + K_d(t).\frac{de(t)}{dt} \quad (6)$$

Where Kp(t), Ki(t) and Kd(t) are time-varying PID gains adjusted by the fuzzy inference system.

The fuzzy system employs two input variables, namely the error *e*(*t*) and the rate of change of the error $e^{\cdot}(t)$, while the outputs are the controller gains K_p, K_i and K_d as illustrated in Figure 5 [7]. This mechanism enables the system to adapt flexibly to variations in the plant dynamics and operating environment.

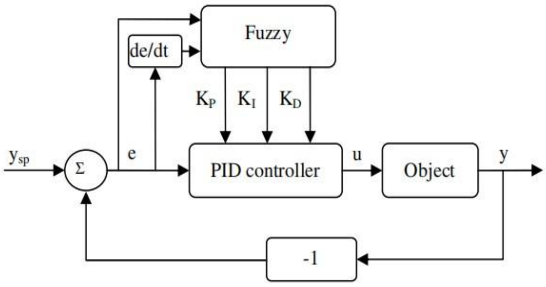


Figure 5. *Overall structure of the adaptive fuzzy–PID controller*

The PID parameters are updated according to the following expression [16]:

$$\begin{aligned} K_p(t) &= K_{p0} + \Delta K_p(t) \\ K_i(t) &= K_{i0} + \Delta K_i(t) \\ K_d(t) &= K_{d0} + \Delta K_d(t) \end{aligned} \qquad (7)$$

In the structure shown in Figure 6, the input and output variables are fuzzified using five linguistic sets {NB, NS, ZO, PS, PB}. These fuzzy sets are defined as follows: NB (Negative Big), NS (Negative Small), ZO (Zero), PS (Positive Small), and PB (Positive Big). The membership functions of the output fuzzy sets are defined using triangular functions [17], expressed as follows:

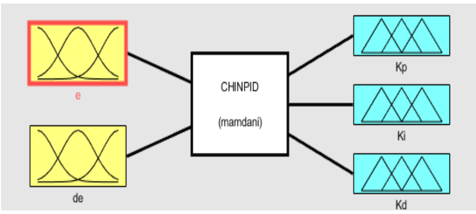


Figure 6. *Structure of the fuzzy controller.*

$$\mu_A(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x < b \\ \frac{x-c}{b-c} & b \le x \le c \\ 0 & x > c \end{cases} \qquad (8)$$

where a, b, and c denote the coordinates of the three vertices of the corresponding triangular fuzzy set A^i.

The fuzzy rule base is constructed based on control experience and the dynamic characteristics of the system. Typical rules include increasing the proportional and derivative gains when both the error and the error rate are large, and reducing the controller gains when the error and its rate are small to avoid oscillations.

Table 2. *Fuzzy Rule Base for* K_p.

e\de	**NB**	**NS**	**ZO**	**PS**	**PB**
NB	PB	PB	PS	PS	ZO
NS	PB	PS	PS	ZO	NS
ZO	PS	PS	ZO	NS	NS
PS	PS	ZO	NS	NS	NB
PB	ZO	NS	NS	NB	NB

Table 3. *Fuzzy Rule Base for* K_i.

e\de	**NB**	**NS**	**ZO**	**PS**	**PB**
NB	NS	NS	NB	NB	NB
NS	NS	ZO	NS	NB	NB
ZO	ZO	PS	PS	NS	ZO
PS	NB	NS	PS	ZO	NS
PB	NB	NB	NS	NS	NS

In Tables 2, 3, and 4 [7], a total of 25 fuzzy rules are defined to adjust K_p, K_i and K_d. The rule base is constructed based on the control error and its rate of change. When the error is large, K_p is increased to enhance the transient response and reduced near the setpoint to limit overshoot. The integral gain K_i is kept small for large errors to prevent integral windup and increased as the error diminishes to eliminate steady-state error.

Table 4. *Fuzzy Rule Base for* K_d.

e\de	***NB***	***NS***	***ZO***	***PS***	***PB***
NB	*PS*	*NS*	*NB*	*NB*	*NB*

The derivative gain K_d is strengthened for high error variation to improve damping and stability, and reduced in steady state to ensure smooth convergence. Based on the fuzzy input variables, the control system employs an if–

NS	*PS*	*ZO*	*NS*	*NB*	*NB*
ZO	*PS*	*ZO*	*ZO*	*ZO*	*NS*
PS	*NB*	*NS*	*NS*	*ZO*	*PS*
PB	*NB*	*NB*	*NB*	*NS*	*PS*

then rule-based inference mechanism to determine the control output.

A typical fuzzy rule can be expressed as follows:

$$IF\ e = NB\ and\ de = NB\ Then\ K_p = PB, K_i = NB, K_d = PS \quad (9)$$

After the inference stage, the fuzzy output is transformed into a crisp value using the centroid defuzzification method [10]. For implementation on the STM32 microcontroller, the continuous integral is approximated by a discrete summation as expressed in (10):

$$\Delta K_x = \frac{\sum_{i=1}^{N} u_i.\mu_U(u_i)}{\sum_{i=1}^{N} \mu_U(u_i)} \quad x \in \{p, i, d\} \quad (10)$$

The proposed fuzzy logic–based PID controller for the DC motor position–speed control system is implemented in an incremental PID form, in which the control signal is computed as follows [16]:

$$\begin{aligned} &\Delta P(t) = \left[K_p^0 + a_1 K_p(t)\right][e(t) - e(t-1)],\\ &\Delta I(t) = \left[K_i^0 + a_2 K_i(t)\right]e(t),\\ &\Delta D(t) = \left[K_d^0 + a_3 K_d(t)\right][e(t) - 2e(t-1) + e(t-2)],\\ &\Delta u(t) = \Delta P(t) + \Delta I(t) + \Delta D(t),\\ &u(t) = \Delta u(t) + u(t-1). \end{aligned} \quad (11)$$

In (11), Δu(t) denotes the variation of the control signal generated by the PID controller at time t. The components ΔP(t), ΔI(t), and ΔD(t) represent the respective incremental contributions of the proportional, integral, and derivative actions. The adaptive gains Kp(t), Ki(t), and Kd(t) are obtained from the fuzzy inference mechanism and adjusted through scaling factors $a1$, $a2$, and $a3$, as described in [16]. The initial parameters K_p^0, K_i^0 and K_d^0 define the nominal operating point of the PID controller.

Figures 7–9 illustrate the fuzzy logic control surfaces of the adaptive PID gains K_p, K_i and K_d. The initial PID gains provide the baseline performance and are then tuned online via fuzzy inference. This tuning mechanism allows the system to respond effectively to varying operating conditions. This approach helps improve the system response and stability, while also reducing the effect of uncertainties and load disturbances compared to a conventional PID controller.

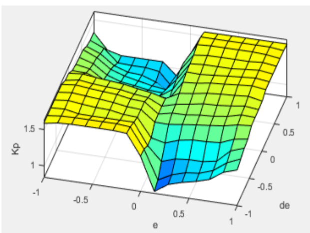


Figure 7. *Fuzzy logic control surface of* K_p.

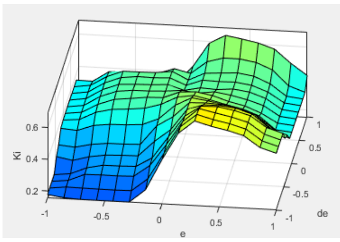


Figure 8. *Fuzzy logic control surface of* K_i.

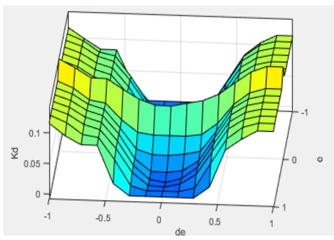


Figure 9. *Fuzzy logic control surface of* K_d.

3. RESULTS AND DISCUSSION

3.1. Simulation results

The DC motor and position control system are modeled in MATLAB/Simulink. Simulations are conducted to evaluate the performance of the proposed fuzzy–PID controller under different operating conditions, including load variations and external disturbances. Different test scenarios are examined, including load torque disturbances, variations in the moment of inertia, as well as no-load and load conditions. The parameters of the DC motor model are listed in Table 1. Under these conditions, the system response is analyzed and compared with that of a conventional PID controller.

For a fair comparison, both controllers are tested under the same operating conditions and disturbance levels. The evaluation focuses on response time, overshoot, settling time, and steady-state error. The controller structures are shown in Figure 10 and Figure 11, while the system performance is assessed based on position and error responses.

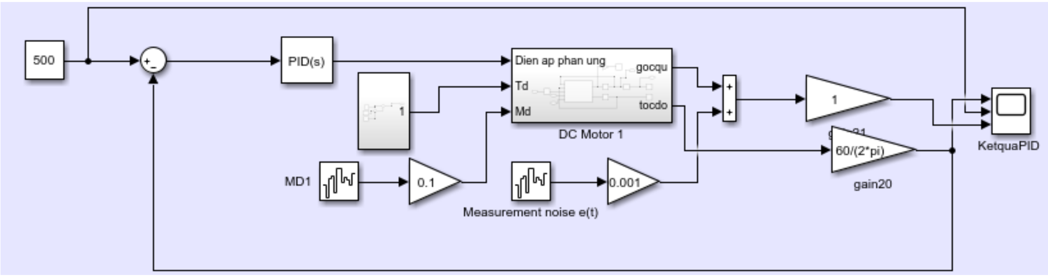
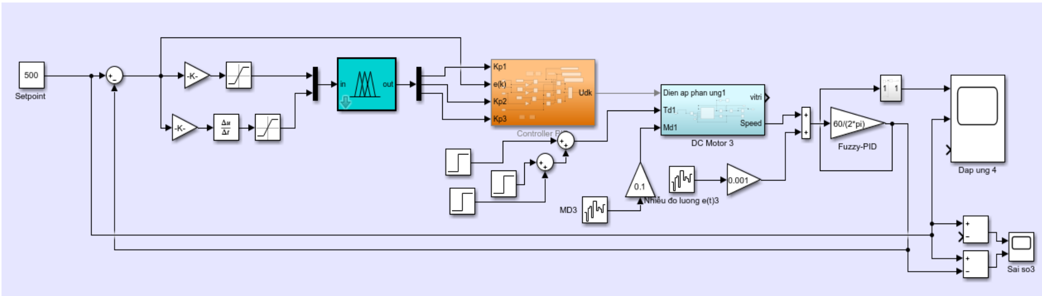


Figure 10. *PID controller model in Simulink.*



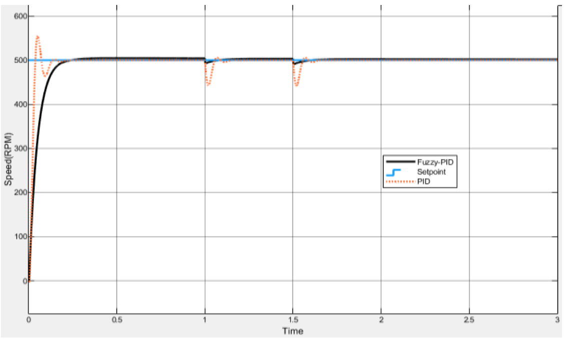


Figure 12. *Speed response at light load (0.5 N·m, 26% rated).*

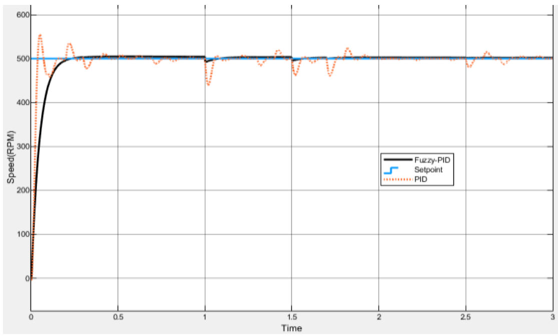


Figure 13. *Speed response with load variation and disturbance.*

In the experiment, the system begins with a light load of 0.5 N·m. The load is then changed at 1 s and 1.5 s, and a disturbance of ± 0.03 N·m is added. The velocity responses can be seen in Figure 12 and Figure 13.

Figure 12 shows that the system responds quickly, with only a small drop in speed under light-load conditions. In Figure 13, the controller handles sudden load disturbances and keeps the system stable with little oscillation. The corresponding control error responses are given in Figure 14.

The system is further tested under a higher load of 1.5 N·m (approximately 70% of the rated torque). Load variations and disturbances are applied at 1s and 1.5 s. A speed drop is observed when the load increases, after which the controller restores stable operation with a small error. The corresponding responses are shown in Figure 15.

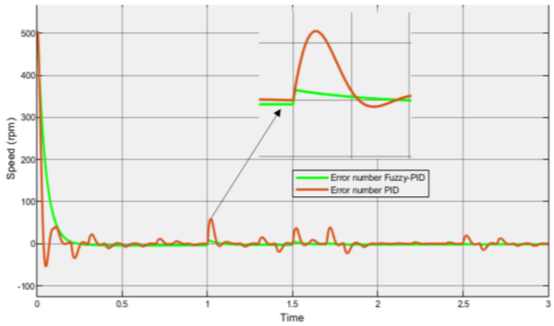


Figure 14. *Error response with load change and disturbance.*

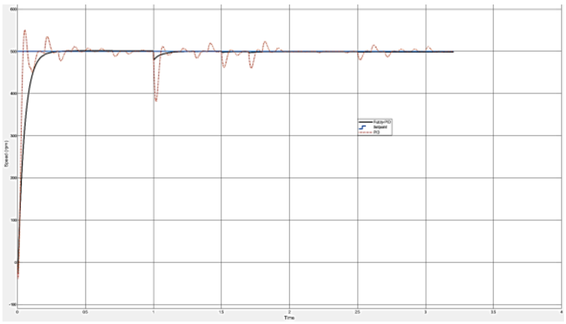


Figure 15. *Motor speed at higher load (1.5 N·m).*

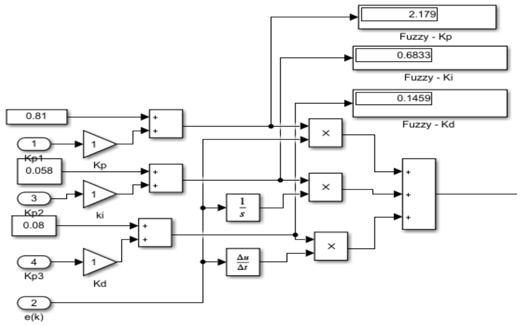


Figure 16. *PID parameters adjusted by fuzzy logic.*

Table 5*. Performance comparison between PID and fuzzy–PID controllers.*

Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)
PID	0.0233	0.119	12.76
Fuzzy–PID	0.1004	0.171	0.85

The simulation results show that the conventional PID controller provides a faster transient response, with a rise time of 0.0233s and a settling time of 0.119s. However, this advantage comes at the cost of a relatively high overshoot of 12.76%, which may lead to unwanted oscillations and increased mechanical stress in the railway barrier mechanism. In comparison, the proposed fuzzy–PID controller significantly suppresses the overshoot to 0.85%, resulting in a more stable and well-damped response. Although the rise time (0.1004 s) and settling time (0.171 s) are slightly increased, the overall behavior of the system becomes smoother and more suitable for safety-oriented applications.

This improvement highlights a clear trade-off between response speed and stability. For railway barrier systems, where reliability and safety are more critical than fast response, the proposed controller provides a more appropriate solution.

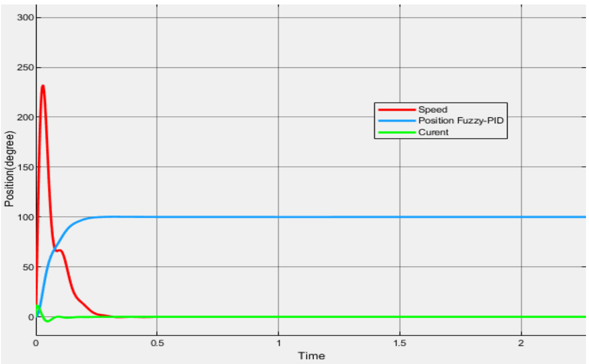


Figure 17. *Responses of position, speed, and current under fuzzy–PID control for a 100° setpoint.*

The system response in Figure 17 illustrates the performance of the proposed fuzzy controller in regulating motor position, speed, and armature current. The results show smooth convergence and reduced oscillations across all state variables, confirming stable operation under dynamic conditions.

When disturbances occur, the conventional PID controller shows clear speed deviations and oscillatory behavior, reflecting its limited robustness under changing load conditions. By contrast, the proposed Adaptive fuzzy–PID controller produces a smoother response, with lower speed deviation and almost no steady-state error. This suggests that the controller is more effective in coping with disturbances and adapting to load variations in the automatic railway barrier system.

3.2. Experimental implementation

The proposed fuzzy–PID controller is implemented on an STM32 microcontroller [13] with a fixed sampling period to evaluate its performance in practice. The controller runs directly on the STM32, where tasks such as encoder signal reading, fuzzy-based PID tuning, and PWM generation for motor control are handled. The overall setup is shown in Figure 18.

Experimental data are sent to an ESP32 via UART and then passed to a web-based platform for monitoring and analysis of the system response [14]. This setup allows practical factors such as computational delay, measurement noise, and signal quantization to be observed and evaluated more clearly.

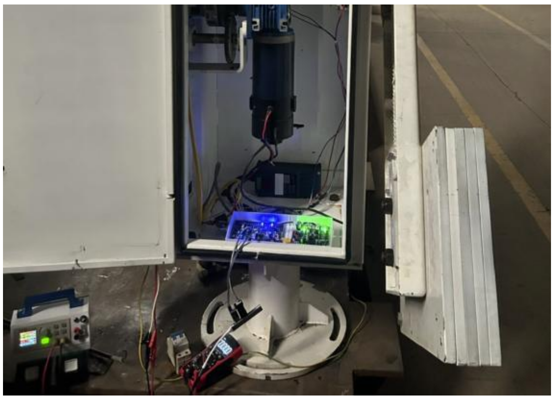


Figure 18. *Embedded setup for DC motor control.*

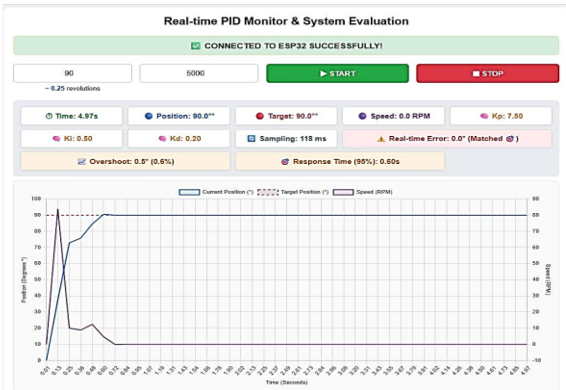


Figure 19. *Position response for a step from 0° to 90°.*

Figure 20. *Position response with disturbance (no load).*

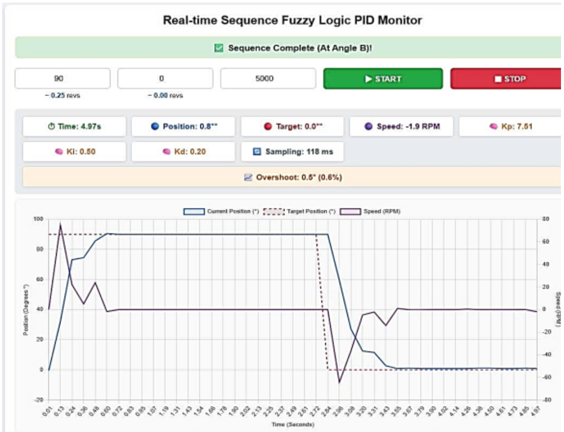


Figure 21. *Position response with disturbance (under load).*

The experimental setup is used to assess the performance of the proposed fuzzy–PID controller.

Figure 19 shows the position response when the reference changes from 0° to 90°. The system reaches the desired position quickly, with only a small overshoot of about 0.5° and a settling time of around 0.6 s, indicating stable and reliable operation.

In the experiment, the system is tested with two reference changes: from 0° to 90° and from 90° back to 0°, so that its response in both directions can be observed. The controller parameters are set to K_p =7.50, K_i = 0.50 and K_d = 0.20. The control algorithm runs on the STM32 using a fast sampling loop for real-time operation. Measurement data are sent to the ESP32 every 20 ms via UART and then updated on the web interface at around 100 ms. With this setup, communication delays have little impact on control performance while still allowing real-time monitoring.

At the beginning, when the control error is still large, the values of K_p, K_i and K_d are continuously adjusted by the fuzzy mechanism. As the system gets closer to the reference position, these parameters gradually settle and remain nearly constant. The experimental results show that the proposed fuzzy–PID controller can track the reference well and maintain stable operation.

4. CONCLUSIONS

This study presented an adaptive fuzzy–PID control method for DC motor position control in an automatic railway barrier system. The controller combines PID control with fuzzy logic to adjust the PID gains during operation. Simulation results show that the fuzzy–PID controller reduces the overshoot from 12.76% to 0.85%, about 93.3%. However, the rise time and settling time are longer, showing a trade-off between response speed and system stability.

The controller was also tested on an STM32 platform. The experimental results show that the system can operate stably under measurement noise, quantization effects, and computational delay. Overall, the proposed fuzzy–PID controller gives better stability and robustness than the conventional PID controller. Future work will focus on improving the fuzzy rules, response speed, and computational efficiency for embedded systems.

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TÓM TẮT

Thiết kế bộ điều khiển fuzzy–PID thích nghi cho hệ thống rào chắn đường sắt tự động sử dụng động cơ DC

Bài báo đề xuất thiết kế bộ điều khiển fuzzy–PID thích nghi cho hệ thống rào chắn đường sắt tự động sử dụng động cơ một chiều. Bộ điều khiển kết hợp PID với logic mờ nhằm điều chỉnh trực tuyến các tham số PID theo sai số điều khiển và tốc độ biến thiên của sai số, từ đó cải thiện hiệu suất hệ thống trong điều kiện phi tuyến, biến thiên tải và nhiễu ngoài.Hệ thống được mô phỏng trên MATLAB/Simulink và triển khai thực nghiệm trên vi điều khiển STM32 cho kiểm chứng thời gian thực. Kết quả cho thấy bộ điều khiển đề xuất giúp giảm độ quá điều chỉnh từ 12.76% xuống 0.85% và cải thiện đáp ứng mượt hơn khi có nhiễu tải. Mặc dù thời gian xác lập tăng nhẹ, hệ thống vẫn bảo đảm tính vận hành tin cậy và khả năng giảm dao động tốt. Các kết quả thực nghiệm cũng cho thấy hệ thống hoạt động ổn định, có khả năng ứng dụng cho hệ thống rào chắn đường sắt thực tế.

Từ khóa: Điều khiển fuzzy–PID; Điều khiển thích nghi; Động cơ một chiều; Hệ thống rào chắn đường sắt tự động; STM32.