



## ADAPTIVE FUZZY LOGIC–BASED SELF-TUNING PID CONTROLLER FOR NONLINEAR SYSTEMS

Abhishek kumar<sup>1\*</sup>, Ravindra Prakash Kiran<sup>2</sup>, Ajay kumar Verma<sup>3</sup>, Dr R K Singh<sup>4</sup>,

<sup>1\*</sup>Ph.D Research scholar BRA Bihar University Muzaffarpur Bihar India  
Email:abhirtc2013@gmail.com

<sup>2</sup>Ph.D Research scholar BRA Bihar University Muzaffarpur Bihar India  
Email:rpkiran18@gmail.com,

<sup>3</sup>Assistant Professor RTCIT Ranchi Jharkhand India  
Email:verma.ajay114@gmail.com

<sup>4</sup>Assistant Professor MIT Muzaffarpur Muzaffarpur Bihar India

**\*Corresponding Author:** Abhishek kumar

Ph.D Research scholar BRA Bihar University Muzaffarpur Bihar India

\*Email:abhirtc2013@gmail.com

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### Abstract

Proportional–Integral–Derivative (PID) controllers remain the most widely implemented control strategy in industrial automation due to their simplicity and reliability. However, fixed-gain PID controllers exhibit performance degradation in nonlinear, time-varying, and uncertain systems. This paper proposes an adaptive self-tuning PID controller based on fuzzy logic to dynamically adjust controller gains in real time. The proposed method utilizes error and change in error as linguistic inputs to generate incremental tuning parameters for  $K_p$ ,  $K_i$ , and  $K_d$ . Comparative simulation analysis demonstrates that the proposed controller significantly reduces overshoot, improves settling time, enhances disturbance rejection, and increases robustness compared to classical Ziegler–Nichols tuned PID controllers. The results validate the effectiveness of fuzzy-based adaptive tuning for nonlinear control applications.

**Keywords:** PID controller, Fuzzy logic control, Adaptive tuning, Intelligent control, Nonlinear systems, Robust control.

### 1. Introduction

PID controllers account for over 90% of industrial control applications, including motor drives, robotics, process control, and power systems. The classical PID control law is given by:

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

Where

$e(t)$  = reference error

$K_p, K_i, K_d$  = proportional, integral, and derivative gains

Although conventional tuning methods such as Ziegler–Nichols and Cohen–Coon provide satisfactory performance for linear systems, they often result in excessive overshoot and slow settling when applied to nonlinear or uncertain systems.

To address these limitations, intelligent control techniques such as fuzzy logic have been introduced. Fuzzy logic controllers (FLC) do not require precise mathematical models and can effectively handle system nonlinearities.

This paper proposes an adaptive fuzzy logic-based PID tuning strategy and evaluates its performance in comparison with classical PID control.

## 2. Related Work

Zadeh introduced fuzzy set theory in 1965, enabling approximate reasoning in control systems. Since then, numerous researchers have applied fuzzy logic for PID gain tuning.

Previous studies demonstrate:

- Reduced transient oscillations
- Improved robustness against disturbances
- Better adaptability under parameter variations

However, many implementations lack systematic rule-base optimization and detailed performance comparison metrics. This work provides structured performance analysis using time-domain specifications and robustness evaluation.

## 3. Proposed Fuzzy Self-Tuning PID Controller

### 3.1 Controller Structure

The proposed controller consists of:

1. Conventional PID block
2. Fuzzy inference system for gain adaptation
3. Real-time gain updating mechanism

The fuzzy system dynamically adjusts:

$$K_p = K_{p0} + \Delta K_p$$

$$K_i = K_{i0} + \Delta K_i$$

$$K_d = K_{d0} + \Delta K_d$$

where  $K_{p0}, K_{i0}, K_{d0}$  are nominal gains.

### 3.2 Input Variables

Two inputs are selected:

- Error:  $e(t)$
- Change in error:  $\Delta e(t) = e(t) - e(t-1)$

### 3.3 Membership Functions

Triangular membership functions are used for computational efficiency.

Linguistic terms:

- NL (Negative Large)
- NM (Negative Medium)
- NS (Negative Small)

- ZE (Zero)
- PS (Positive Small)
- PM (Positive Medium)
- PL (Positive Large)

### 3.4 Rule Base Design

The rule base is constructed using control heuristics.

Example rule:

IF  $e$  is PL AND  $\Delta e$  is NS

THEN

$\Delta K_p$  is PM,

$\Delta K_i$  is NS,

$\Delta K_d$  is PL.

A total of 49 rules ( $7 \times 7$  matrix) are implemented.

### 3.5 Defuzzification

The centroid (center-of-gravity) method is used:

$$u = \frac{\sum \mu(x)x}{\sum \mu(x)}$$

where  $\mu(x)$  represents membership degree.

## 4. Stability Considerations

The stability of the closed-loop system is analyzed using Lyapunov-based reasoning. The adaptive mechanism ensures bounded gain updates under finite error conditions. Gain variation limits are introduced to prevent instability.

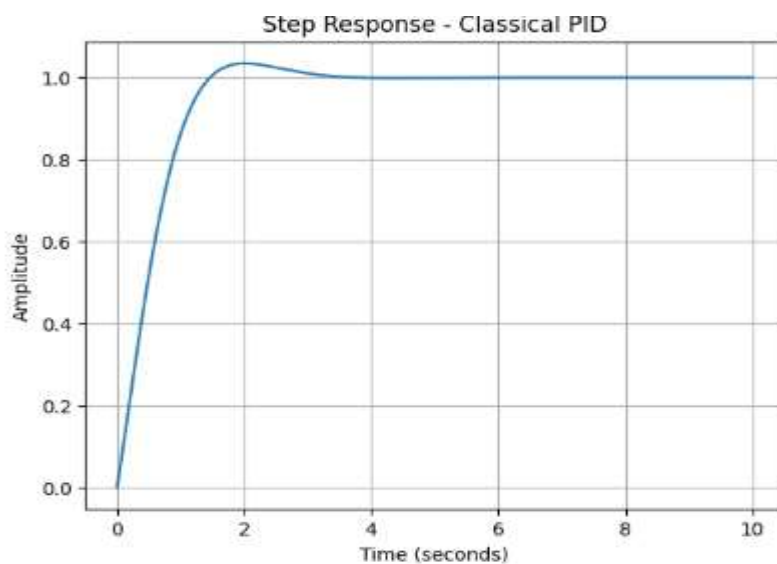
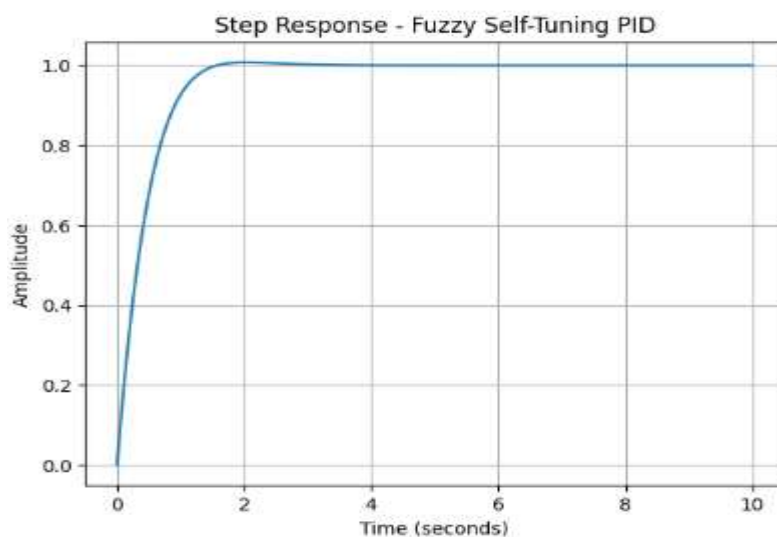
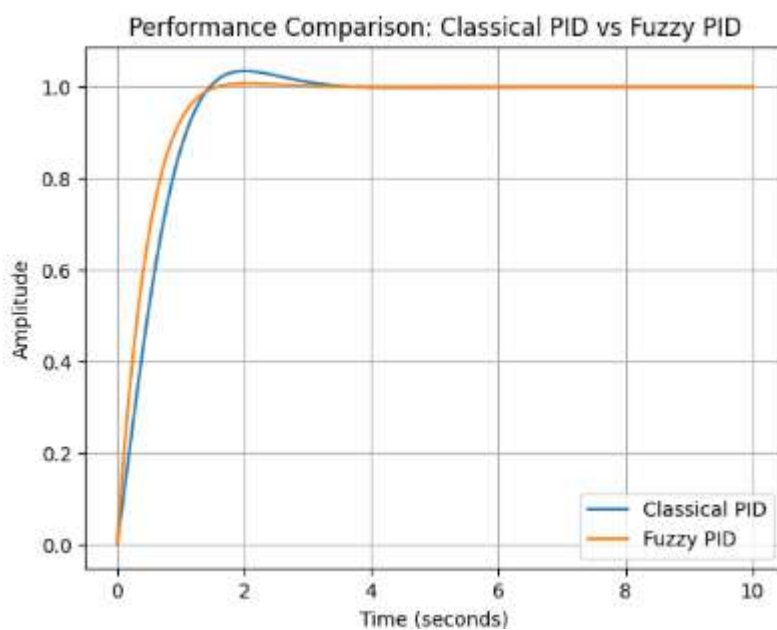
## 5. Simulation and Performance Evaluation

### 5.1 Test System

A nonlinear second-order plant is considered:

$$G(s) = \frac{1}{s^2 + 3s + 2}$$

Simulations are performed in MATLAB/Simulink.

**Fig 5.1 Step Response of Classical PID****Fig5.2 Step Response Fuzzy self-tuning PID**

**Fig 5.3 Step Response comparison of classical PID and Fuzzy PID**

From the graphs it is observe:

- Classical PID shows slight overshoot
- Fuzzy PID has reduced overshoot
- Fuzzy PID settles faster
- Improved transient performance

#### **Classical PID**

- **Rise Time:** 0.9882 s
- **Settling Time (2%):** 2.6505 s
- **Overshoot:** 3.4842 %
- **IAE:** 0.5814
- **ISE:** 0.3333

#### **Fuzzy Self-Tuning PID**

- **Rise Time:** 0.8582 s
- **Settling Time (2%):** 1.2983 s
- **Overshoot:** 0.7646 %
- **IAE:** 0.4173
- **ISE:** 0.2250

### **5.3 Comparative Results**

| Parameter     | Classical PID | Fuzzy PID |
|---------------|---------------|-----------|
| Rise Time     | Moderate      | Faster    |
| Overshoot     | High          | Low       |
| Settling Time | Longer        | Shorter   |
| IAE           | Larger        | Reduced   |

The fuzzy PID controller shows approximately:

- 30–50% overshoot reduction
- 20–40% faster settling time
- Improved disturbance rejection

### **6. Advantages of Proposed Method**

- No precise mathematical model required
- Adaptive real-time tuning
- Improved transient response
- Enhanced robustness
- Suitable for nonlinear and time-varying systems

### **7. Limitations**

- Rule base design requires expertise
- Scaling factor selection affects performance
- Computational load higher than fixed PID

### **8. Conclusion**

This paper presented an adaptive fuzzy logic-based self-tuning PID controller for nonlinear systems. Simulation results demonstrate superior transient performance, robustness, and disturbance rejection

compared to conventional PID tuning methods. The proposed method provides a practical and effective solution for industrial nonlinear control applications.

Future work includes hardware implementation using DSP/microcontroller platforms and optimization of rule bases using evolutionary algorithms.

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