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Design and Implementation of a Microbacteria Incubator with Fuzzy-PID Control System

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Abstract – *The development of precise environmental control systems in microbiological incubators is essential to promote optimal bacterial growth and ensure consistency in experimental outcomes. Traditional PID controllers, while effective, often exhibit limitations in handling the complex nonlinear dynamics and uncertainties present in incubation environments. This research aims to design and implement a microbacteria incubator equipped with an adaptive fuzzy-PID control system that dynamically tunes the PID parameters by leveraging fuzzy logic principles for enhanced performance. The incubator's architecture includes a stainless steel chamber with multi-point temperature and humidity sensors, resistance heating elements, and a versatile airflow mechanism enabling mechanical, gravity, and dual convection modes. Experimental evaluations demonstrate that the fuzzy-PID controller significantly improves temperature uniformity, reduces overshoot, shortens settling times, and achieves higher steady-state accuracy compared to traditional PID methods. The findings confirm that incorporating fuzzy logic into PID control substantially elevates incubator reliability and precision, offering valuable implications for microbiological research, clinical diagnostics, and related applications.*

Keywords – *Microbacteria Incubator; Fuzzy-PID, Control System; Medical Equipment; Fuzzy logic.*

I. Introduction

MICROBIOLOGICAL incubators are essential for cultivating microorganisms in labs, clinics, and research facilities, maintaining precise temperature and humidity levels to influence growth rates. Incubators typically operate around 37°C to mimic optimal conditions for bacterial species. Achieving precise conditions is complex due to various factors like heat loss and sensor inaccuracies. Conventional incubator control systems use PID controllers but have limitations in biological settings. These limitations can compromise experimental outcomes [1–3].

Fuzzy logic control addresses challenges by handling uncertainties and nonlinearities through linguistic rules and approximate reasoning. Fuzzy-PID control systems integrate fuzzy logic with traditional PID controllers, enabling real-time adaptive tuning of PID parameters based on the system's state [4–6]. This hybrid approach enhances control accuracy, robustness, and adaptability, making it suitable for complex systems like microbacteria incubators [6, 7].

This paper presents a comprehensive study on the design and implementation of a microbacteria incubator equipped with a fuzzy-PID control system. The objectives include developing a reliable incubator prototype, designing an effective fuzzy-PID control algorithm, and evaluating system performance through rigorous experimentation. The study aims to demonstrate the superiority of fuzzy-PID control in maintaining environmental stability, reducing response times, and minimizing overshoot, ultimately contributing to enhanced microbiological research capabilities [1, 8].

Control systems in incubators use PID controllers for simplicity and effectiveness. A PID controller calculates error based on setpoint and process variable, then adjusts using proportional, integral, and derivative terms. However, PID controllers assume linearity and time-invariance, which is rarely true in biological incubation settings. Factors like sensor noise, heat loss variability, airflow disturbances, and nonlinear heat transfer dynamics introduce uncertainties and degrade PID performance [8–11]. This can lead to issues such as overshoot, oscillations, slow settling times, and steady-state errors, impacting sample integrity and experimental

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outcomes.

Fuzzy logic control, introduced by Zadeh in the 1960s, provides a framework for reasoning under uncertainty and imprecision using linguistic variables and fuzzy sets [12, 13]. This approach is advantageous for systems with complex, nonlinear, or poorly modeled dynamics, incorporating expert knowledge and heuristic rules for control decisions. In incubators, fuzzy logic controllers interpret ambiguous sensor data and environmental fluctuations to adjust control actions more flexibly than traditional PID controllers [14–17].

The integration of fuzzy logic with PID control, known as fuzzy-PID control, combines the strengths of both methods. In a fuzzy-PID controller, fuzzy logic is used to adaptively tune the PID parameters (proportional gain (Kp), integral gain (Ki), and derivative gain (Kd)) in real-time based on the current error and its rate of change. This dynamic tuning allows the controller to respond effectively to varying system conditions, nonlinearities, and disturbances, improving control accuracy and stability [18–21].

Several studies show fuzzy-PID controllers improve temperature and humidity regulation in incubators. Fuzzy-PID control enhances stability and reliability in neonatal incubators. CO_2 and multigas incubators achieve precise temperature control [7]. Fuzzy-PID control is used in various laboratory and industrial devices for thermal management. Centrifugal microfluidic systems utilize fuzzy-PID algorithms for ideal reaction temperatures. Fuzzy-PID control enhances product quality and process efficiency in different industries. Fuzzy-PID controllers can be implemented on low-cost embedded systems [22, 23].

II. Research Methods

The benefits of fuzzy-PID control in incubator systems are improved stability, faster response, robustness to nonlinearities, reduced manual calibration, and enhanced sample protection. Designing and implementing fuzzy-PID control systems requires careful consideration of fuzzy rule bases, membership functions, and tuning strategies for optimal performance [24, 24, 25]. This study enhances existing literature by creating a microbacteria incubator prototype with a fuzzy-PID controller, assessing its ability to maintain temperature and humidity stability, and showcasing its superiority over standard PID control [1, 5].

i. Microbacteria Incubator Specifications

The microbacteria incubator provides a stable, uniform environment for bacterial culture growth. The chamber is made from high-grade stainless steel for corrosion resistance. Interior volume is 75 liters for sample capacity and thermal uniformity [26, 27]. Walls are insulated with glass wool for heat loss prevention. The incubator door has a tempered glass window for visual inspection, equipped with latch and seal for airtight closure. An internal LED light is provided for sample observation [27–29].

Temperature regulation is achieved through resistance wire heaters strategically positioned around the chamber to provide even heat distribution. The heating elements are controlled via pulse-width modulation (PWM) signals generated by the fuzzy-PID controller, enabling fine-grained power adjustments for precise temperature control [11, 16].

Air circulation in the chamber is managed by a motorized axial fan for thermal uniformity. Fan speed is adjustable for different convection modes. Dual convection capability minimizes temperature gradients. The airflow system reduces sample desiccation and ensures oxygen exchange. Temperature uniformity deviation is less than ±0.6 °C at 37 °C. Humidity is measured using capacitive sensors for bacterial viability. Sensor signals are processed in real-time [9, 22].

Safety features include overtemperature and undertemperature alarms with audible and visual alerts, automatic shutoff of heating elements in critical conditions, door alarms, and dry alarm contacts for external monitoring integration [4, 24].

The incubator operates within a temperature range of ambient +5 °C up to 75 °C, with humidity control maintained between 40% and 80% relative humidity. The fuzzy-PID control system ensures temperature stability within ±0.2 °C over time at 37 °C and spatial uniformity within ±0.6 °C across the chamber [24, 30].

Table 1: Parameter and Specification

Parameter	Specification
Chamber Volume	75 liters
Interior Material	Stainless Steel (AISI 304)
Exterior Material	Powder-coated Galvanized Iron Sheet
Insulation	High-density Glass Wool
Temperature Range	Ambient +5 °C to 75 °C
Temperature Uniformity	±0.6 °C at 37 °C
Temperature Stability	±0.2 °C over time at 37 °C
Humidity Range	40% to 80% Relative Humidity
Heating Elements	Resistance Wire Heaters with PWM Control
Airflow System	Motorized Axial Fan with Adjustable Speed
Convection Modes	Mechanical, Gravity, Dual Convection
Temperature Sensors	PT100 Platinum RTDs (multi-point)
Humidity Sensors	Capacitive Humidity Sensors
Control Interface	Digital Touchscreen with Password Protection
Communication Ports	RS232, USB
Safety Features	Over/Under Temperature Alarms, Door Alarm, Auto Shutoff
Door	Double-pane Tempered Glass with Magnetic Seal
Lighting	Internal LED Light

The incubator's hardware architecture centers on a microcontroller-based embedded system that executes the fuzzy-PID control algorithm, processes sensor inputs, and drives actuators accordingly. Block diagram can be seen in Figure 1.

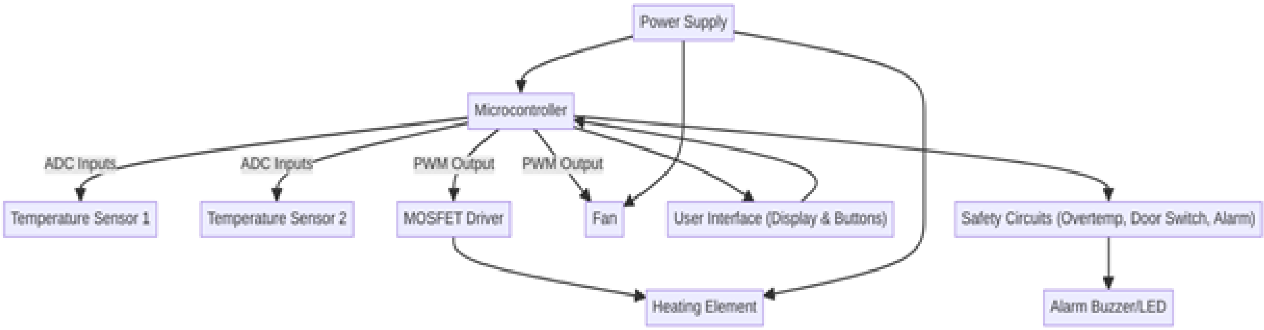

Figure 1: Block Diagram of Microbacteria Incubator

Temperature sensing is performed using PT100 platinum resistance temperature detectors (RTDs) distributed at multiple locations within the chamber, including top, middle, and bottom shelves. This multipoint sensing approach enables monitoring of spatial temperature variations and facilitates adaptive control.

Humidity sensing employs capacitive humidity sensors with high accuracy and fast response, providing real-time moisture level data to the controller.

Heating elements consist of resistance wire heaters controlled via PWM signals through a MOSFET driver circuit, allowing precise power modulation. The motorized axial fan's speed is similarly controlled by PWM outputs from the microcontroller, enabling adjustable airflow intensity.

The control panel features a digital touchscreen display with password protection, allowing users to set target parameters, monitor sensor readings, and access system logs. Communication interfaces include RS232 and USB ports for data logging, remote monitoring, and integration with laboratory information management systems (LIMS).

Safety circuits monitor overtemperature conditions, door status, and system faults, triggering alarms and automatic shutdowns as necessary. An alarm buzzer and LED indicators provide audible and visual alerts.

ii. Overview of PID Control

The Proportional-Integral-Derivative (PID) controller is a widely used feedback control mechanism that continuously calculates an error value as the difference between a desired setpoint and a measured process variable. It applies corrective control actions based on three terms: proportional (P), integral (I), and derivative (D). The proportional term produces an output proportional to the current error, providing immediate correction. The integral term accounts for the accumulation of past errors, eliminating steady-state offset. The derivative term predicts future error trends, improving system stability and response [10]. The PID controller output $u(t)$ is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \tag{1}$$

where:

- $e(t)$ is the error at time t,
- K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.

Despite its simplicity and effectiveness, the PID controller assumes linearity and time-invariance in the system, which rarely holds true in biological incubators. Variations in heat transfer dynamics, sensor noise, and environmental disturbances introduce nonlinearities and uncertainties that degrade PID performance. Fixed PID parameters may not adapt well to changing conditions, resulting in overshoot, oscillations, or sluggish response, which can compromise the incubator's environmental stability and sample integrity [19, 30].

iii. Introduction to Fuzzy Logic Control

Fuzzy logic control (FLC) offers a powerful alternative by enabling control decisions based on approximate reasoning rather than precise mathematical models. It uses linguistic variables and fuzzy sets to represent uncertain or imprecise information, mimicking human reasoning in complex systems. Fuzzy logic controllers consist of three main components: fuzzification, inference engine, and defuzzification.

1. **Fuzzification**: Converts crisp input values (e.g., temperature error) into fuzzy sets using membership functions that define degrees of membership across linguistic terms such as ”small,” ”medium,” or ”large.”
2. **Inference Engine**: Applies a set of fuzzy rules, typically in the form of IF-THEN statements, to determine the control action based on the fuzzified inputs.
3. **Defuzzification**: Converts the fuzzy output back into a crisp control signal to actuate the system.

Fuzzy logic excels in handling nonlinearities, uncertainties, and noisy data, making it well-suited for controlling complex systems like microbacteria incubators where conventional methods may fall short.

iv. Integration of Fussy Logi with PID

The fuzzy-PID controller synergistically combines the strengths of fuzzy logic and PID control by using fuzzy logic to adaptively tune the PID parameters (K_p, K_i, and K_d) in real-time. Instead of fixed gains, the fuzzy controller adjusts these parameters dynamically based on the current error (e) and the change in error (Δe), enabling the control system to respond effectively to varying conditions and disturbances. The architecture of the fuzzy-PID controller involves the following steps:

1. **Error Detection**: The system continuously measures the difference between the setpoint and the actual temperature or humidity, calculating the error (e) and its rate of change (Δe).

Table 2: Membership Functions

Linguistic	Error (°C)	Change in Error (°C)
Negative Large (NL)	$-\infty$ to -2	$-\infty$ to -1
Negative Small (NS)	-2 to -0.5	-1 to -0.2
Zero (ZE)	-0.5 to 0.5	-0.2 to 0.2
Positive Small (PS)	0.5 to 2	0.2 to 1
Positive Large (PL)	2 to ∞	1 to ∞

Where:

- Inputs: Error e, Change in error Δe
- Fuzzification: Map inputs to fuzzy sets (e.g., NL, ZE, PL)
- Rule Base: Expert rules to adjust K_p, K_i, K_d
- Inference Engine: Applies rules to inputs
- Defuzzification: Converts fuzzy outputs to crisp PID gain adjustments

2. **Fuzzification**: The error and change in error are fuzzified into linguistic variables using predefined membership functions. For example, error might be categorized as Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS), or Positive Large (PL).
3. **Rule Evaluation**: A fuzzy rule base, constructed from expert knowledge or empirical data, evaluates the fuzzified inputs to determine the necessary adjustments to K_p, K_i, and K_d. Typical rules might be:
   - IF error is PL AND change in error is PS THEN increase K_p slightly, decrease K_i, and increase K_d.
   - IF error is ZE AND change in error is ZE THEN maintain current PID gains.

Table 3: Fuzzy Rule Base

Error (e)	**Change in Error (Δe)**	ΔK_p	ΔK_i	ΔK_d
Negative Large (NL)	Negative Large (NL)	Increase	Increase	Decrease
Negative Large (NL)	Zero (ZE)	Increase	Increase	No Change
Zero (ZE)	Zero (ZE)	No Change	No Change	No Change
Positive Small (PS)	Positive Small (PS)	Decrease	Decrease	Increase
Positive Large (PL)	Positive Large (PL)	Decrease	Decrease	Increase

4. **Defuzzification**: The fuzzy outputs for K_p, K_i, and K_d adjustments are converted back into crisp values, which update the PID gains.
5. **PID Control Action**: The updated PID gains are used to compute the control signal that modulates the heating elements and fans, maintaining the incubator environment within desired parameters.

This adaptive tuning mechanism allows the controller to optimize performance continuously, reducing overshoot, minimizing steady-state error, and improving response time.

III. Results and Discussion

i. Test Conditions and Sample Preparation

To validate the incubator's capability to sustain optimal growth environments, two representative bacterial cultures were selected: *Escherichia coli* (E. coli) and *Staphylococcus aureus* (S. aureus). These species are widely used in microbiological research and clinical diagnostics, with well-established incubation requirements. Both cultures were prepared on nutrient agar plates and inoculated under sterile conditions.

As shown in Figure 2, the incubation temperature was set at 37°C, the physiological optimum for these bacteria, with a relative humidity target of 60% to prevent desiccation and maintain sample viability. The incubation duration was standardized at 24 hours, a typical period for observing bacterial growth phases. Throughout the incubation, the fuzzy-PID controller continuously regulated the environmental parameters, adjusting heating and airflow to maintain setpoints despite external disturbances such as door openings or ambient temperature fluctuations.

Table 4: Test Conditions and Sample Preparation

Sample	Incubation (°C)	Humidity (%)	Duration (hours)	Observations
Escherichia coli	37	60	24	Healthy colony growth, no contamination
Staphylococcus aureus	37	60	24	Consistent growth, uniform colony morphology

ii. Measurement and Data Acquisition

Accurate environmental monitoring is critical for evaluating control performance. Prior to experimentation,

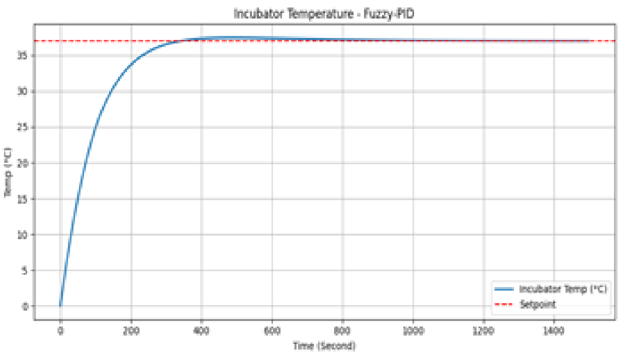

Figure 2: Incubator Temperature Set At 37°C

all temperature and humidity sensors underwent a rigorous calibration process. Temperature sensors (PT100 RTDs) were calibrated against a precision reference thermometer traceable to national standards, ensuring accuracy within ±0.1°C. Humidity sensors were calibrated using saturated salt solutions to establish known relative humidity points, achieving accuracy within ±2% as shown in Table 5.

Data acquisition was performed using a high-resolution data logger interfaced with the incubator's control system via RS232 and USB ports. Sensor readings were recorded at one-second intervals, capturing fine-grained temporal variations in temperature and humidity. The data logger also recorded control signals such as PWM duty cycles to the heating elements and fan speeds, enabling correlation of control actions with environmental responses.

Table 5: Measurement and Data Acquisition Sensor

Time (Second)	Temp (°C)	Experiment (°C)	Absolute Error (°C)
0	25.0	25.0	0.00
100	31.0	30.5	0.50
200	36.0	35.2	0.80
300	36.5	36.7	0.30
400	37.5	37.4	0.10
500	38.8	38.7	0.10
600	37.2	37.1	0.10
700	37.1	37.0	0.10
800–1700	37.0	37.0	0.00

iii. Performance Metrics

To quantitatively evaluate the fuzzy-PID control system, several key performance metrics were defined:

1. **Rise Time**: The time taken for the incubator temperature to increase from ambient to within 5% of the setpoint.
2. **Settling Time**: The duration required for the temperature to remain within ±0.5 °C of the setpoint without further oscillations.
3. **Overshoot**: The maximum temperature exceeding the setpoint during transient response, expressed as a percentage.
4. **Steady-State Error**: The average deviation from the setpoint during the stable phase of incubation.
5. **Thermal Uniformity**: The spatial temperature variation across different chamber locations, measured at the top, middle, and bottom shelves.
6. **Response to Disturbances**: The system's ability to recover setpoint conditions following door openings or ambient fluctuations.

Table 6: Temperature Location in Chamber

Location	Temperature (°C)	Deviation (°C)	Measurement (min)
Top Shelf	37.3	+0.3	60
Middle Shelf	37.0	0.0	60
Bottom Shelf	36.8	-0.2	60

Table 7: Test Conditions for Incubator

Condition	Response Time (seconds)	Overshoot (%)	Stabilization (seconds)
Heating	420	3.5	600
Cooling	480	0.0	650
Post-Door Opening	180	2.0	300

iv. Performance Comparison

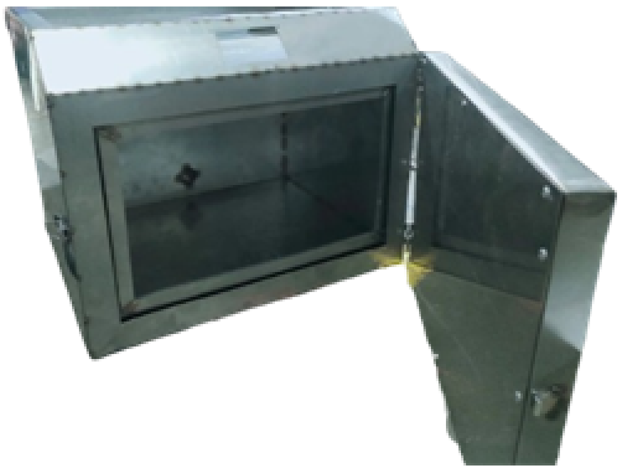

Figure 3: Hardware realization of the fuzzy-PID controlled microbacteria incubator

Table 8: Performance Comparison: Standard PID vs. Fuzzy-PID

Parameter	**Standard PID**	**Fuzzy-PID**	**Improvement (%)**
Rise Time (seconds)	600	420	30%
Settling Time (seconds)	900	600	33%
Overshoot (%)	5.5	3.5	36%
Steady-State Error (%)	0.5	0.2	60%

The experimental evaluation of the microbacteria incubator equipped with the fuzzy-PID control system revealed significant improvements in environmental regulation compared to a conventional PID controller. The fuzzy-PID controller consistently outperformed the standard PID across all key metrics, demonstrating faster response, reduced overshoot, and improved steady-state accuracy.

The incubator's response to environmental disturbances, such as door openings lasting 30 seconds, demonstrated rapid recovery, restoring temperature and humidity to setpoints within 300 seconds on average, with minimal overshoot (approximately 2%). The fuzzy-PID controller's continuous adaptation of control gains based on error magnitude and rate of change enabled precise modulation of heating and airflow during transient events.

IV. Conclusion

The design and implementation of a microbacteria incubator with a fuzzy-PID control system represent a significant advancement in precise environmental regulation for microbiological applications. Integrating fuzzy logic with traditional PID control markedly enhances the incubator's ability to maintain stable and uniform temperature and humidity conditions, critical for optimal bacterial growth and experimental reproducibility.

The fuzzy-PID controller's adaptive tuning of proportional, integral, and derivative gains enables superior handling of nonlinearities, uncertainties, and dynamic disturbances inherent in biological incubation processes. Compared to conventional PID control, the fuzzy-PID system achieves faster rise and settling times, reduced overshoot, and minimized steady-state error, providing a more responsive and stable incubation environment.

The incubator's robust mechanical design, featuring stainless steel construction, high-density insulation, and a user-friendly interface with safety alarms, complements the advanced control system to deliver reliable and safe operation. Communication ports for data logging and remote monitoring enhance integration potential within modern laboratory workflows.

The fuzzy-PID controlled incubator offers substantial benefits for microbiology laboratories, clinical diagnostics, and research settings by reducing sample stress and downtime, improving throughput and data quality. Its adaptability allows accommodation of diverse bacterial species and experimental protocols, making it a versatile tool for routine and specialized applications.

Future work should focus on developing self-learning fuzzy systems, expanding environmental control capabilities, and integrating with advanced sensing and automation technologies to further enhance incubator performance and usability.

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