

Research on the Optimization of PID Temperature Control for High-Precision Applications

Junze Yao *

International Department Urumqi Foreign Languages School, Urumqi, China

* Corresponding Author Email: yjz@xjmstz.org.cn

Abstract. This paper reviews the fundamental model, experimental methods, and achievable control performance of traditional Proportional-Integral-Derivative (PID) temperature control. Building on this foundation, it further investigates multi-module coordination and algorithm optimization to enhance the response speed, accuracy, and adaptability of industrial temperature control systems. The study integrates the flexibility of fuzzy control with the high-precision characteristics of the PID algorithm and explores intelligent PID temperature control schemes, such as the control logic of fuzzy PID controllers. Additionally, it analyzes relevant application cases, particularly the application of the Adaptive Neuro-Fuzzy Inference System (ANFIS) combined with incremental PID in radiofrequency ablation (RFA) temperature control. Compared to traditional PID control systems, this method demonstrates superiority in high-precision applications, such as fiber optic gyroscope temperature control and LED thermal management, and provides a robust solution that combines theoretical and practical approaches for complex thermal environments. Through multi-module coordination and algorithm optimization, this research effectively improves the performance of industrial temperature control systems and offers new perspectives for the advancement of precise temperature control technology.

Keywords: PID temperature control, multi-module collaboration, algorithm optimization, fuzzy control.

1. Introduction

With the development of modern society, advancements in technology, and the widespread adoption of communication networks, the demand for temperature control in industrial automation has been increasing. Due to its stability and effectiveness, the Proportional-Integral-Derivative (PID) temperature control system has been widely applied in industrial temperature regulation. However, traditional PID temperature control systems face certain challenges in mathematical modeling and encounter various limitations in other application domains. For example, maintaining temperature consistency under different operating conditions is crucial for ensuring comfort, improving energy efficiency, and meeting safety standards [1].

Although traditional PID controllers are widely used, their control performance is often inadequate in nonlinear, time-varying, and uncertain environments, and complex systems usually require extensive parameter tuning. In industrial production processes, temperature is often a critical factor influencing production. Temperature variations during production typically exhibit characteristics such as nonlinearity, hysteresis, and high inertia. Accurately modeling such a nonlinear and complex system is challenging. Traditional PID control requires a high degree of model accuracy, which makes it difficult to meet the temperature control demands of production processes when relying solely on conventional PID control. Moreover, standard temperature control methods based on basic thermostats or traditional PID control often suffer from oscillations, overshoot, and long response times. In recent years, research on intelligent PID control has provided new approaches for PID parameter optimization, significantly improving control accuracy. Currently, researchers have integrated fuzzy control theory into traditional PID controller designs, resulting in fuzzy PID controllers that enhance system control performance to some extent.

Fuzzy PID controllers exhibit strong adaptability, allowing them to maintain stable control performance even when system parameters change or environmental conditions fluctuate. Additionally, their robustness and dynamic response characteristics further enhance temperature

control capabilities. For instance, fuzzy logic controllers (FLCs) demonstrate smoother and more adaptive regulation in complex and nonlinear thermal dynamic environments [2].

Therefore, based on an understanding of the fundamental principles of PID control, this paper explores several novel PID temperature control system models to improve temperature control accuracy and adaptability.

2. Fundamental Principles of PID Control

2.1. Overall Design of the PID Temperature Control System

PID temperature control is a classical control algorithm widely used in industrial control applications. Its fundamental principle is to regulate system temperature through a feedback mechanism, ensuring stability at a predefined setpoint. The PID control consists of three primary components: Proportional (P), Integral (I), and Derivative (D). Proportional control (P) adjusts the control output based on the current temperature error, providing a fast response but potentially introducing steady-state error. Integral control (I) accumulates errors over time and compensates for them, eliminating steady-state error and improving system accuracy. Derivative control (D) predicts the trend of error changes and provides feedforward adjustment to suppress overshoot caused by rapid variations. By properly tuning the P, I, and D parameters, a balance can be achieved between response speed, stability, and accuracy. The PID temperature control system consists of the following modules: temperature acquisition module, temperature setting module, MCU control module, external storage module, alarm module, motor drive module, and temperature display module. The overall system block diagram is shown in Figure 1.

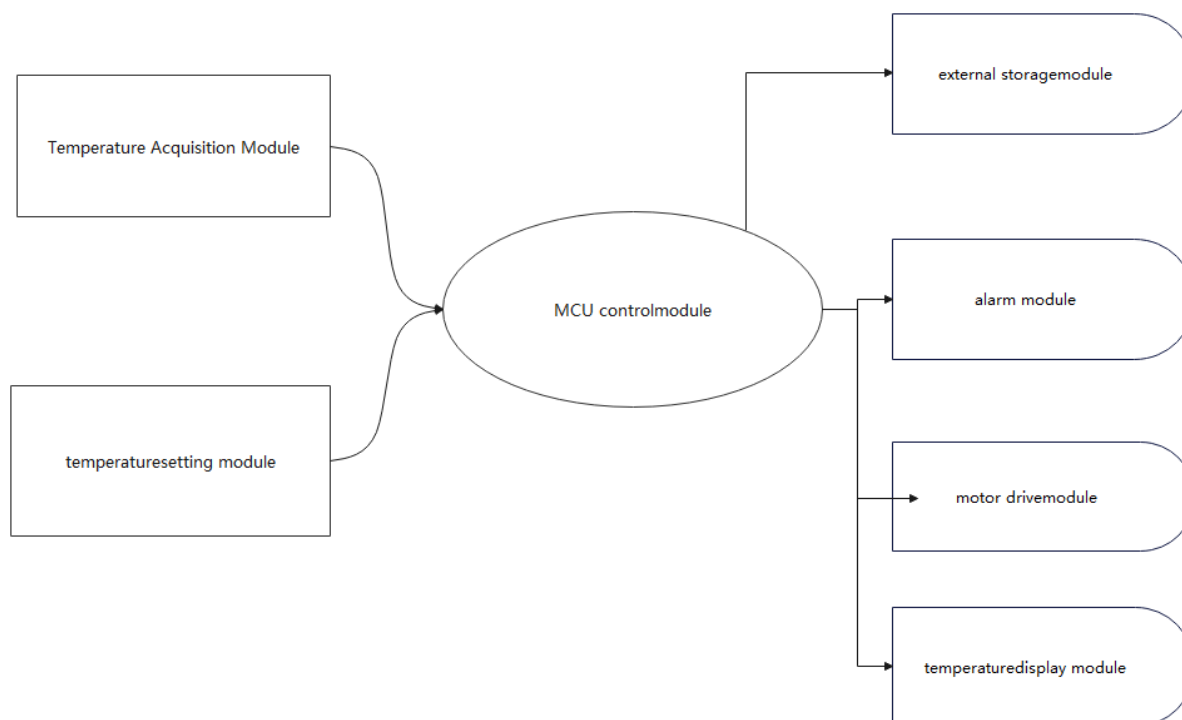


Figure 1. Overall block diagram of PID control system

In terms of temperature control, the system not only displays the current set temperature and performs temperature detection but also transmits the detected object's temperature to the microcontroller. Additionally, a temperature limit alarm module is configured: when the displayed temperature exceeds or falls below the set value, an alarm is triggered to enhance human-machine interaction. Other key components include: first, the MCU module, which operates other system modules and serves as the most critical part of the PID temperature control system; second, the motor drive, consisting of a heating device and a cooling system; and third, the external storage, which

stores the maximum and minimum set temperature values. Using Proteus, a general circuit diagram was constructed, incorporating components such as a microcontroller, crystal oscillator circuit, button circuit, display circuit, reset circuit, temperature sensor, and cooling circuit. The circuit diagram is shown in Figure 2.

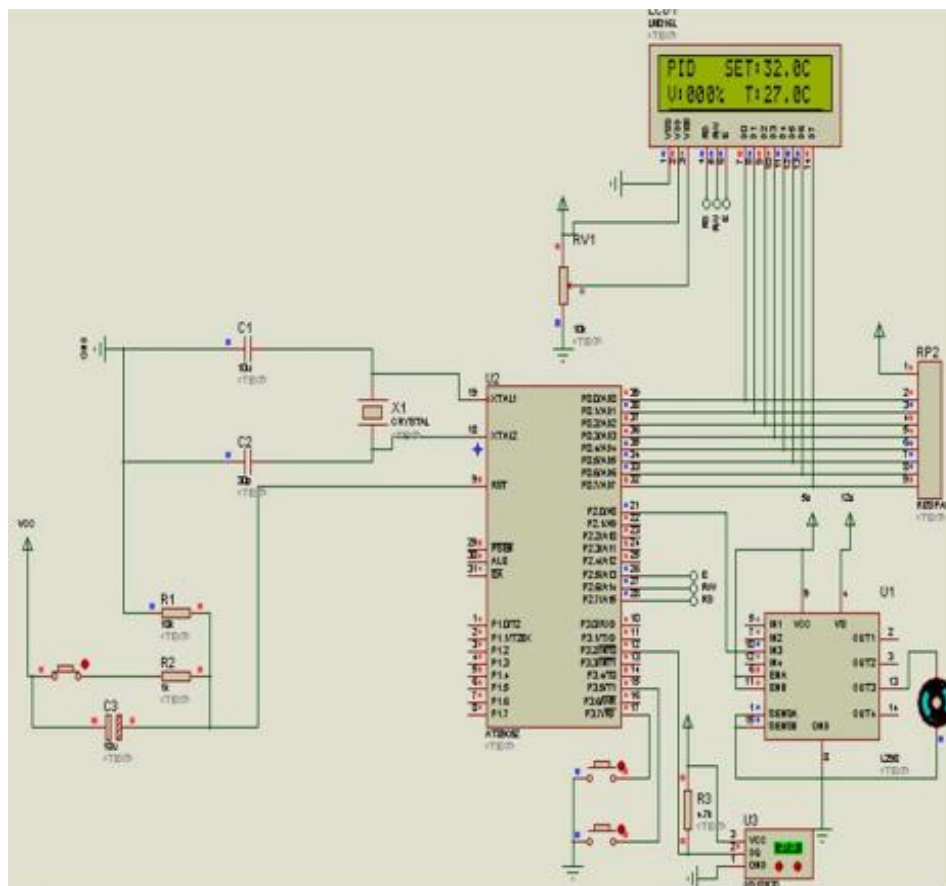


Figure 2. PID system circuit diagram

The MCU serves as the control core of the circuit, while the crystal oscillator circuit provides functional support, such as supplying a working frequency to the MCU, enabling it to quickly recover from fault states. Additionally, the reset circuit plays an indispensable role in the system. When the MCU encounters a malfunction or freezes, the reset circuit allows it to perform system initialization.

In this circuit, the display circuit is responsible for presenting various types of information, including the preset system temperature and the collected temperature, facilitating real-time monitoring by operators. The temperature sensor is used for temperature acquisition, collecting real-time data that is transmitted to the MCU for analysis and processing. There are two possible scenarios: If the current temperature exceeds the preset value, the MCU analyzes the data and issues a command to the cooling circuit, which then executes the command to lower the system temperature to the desired level. Conversely, if the current temperature is lower than the present value, the system initiates heating to reach the required temperature.

3. Case Study of Advanced PID Temperature Control Applications

3.1. Introduction to a Fuzzy PID Temperature Controller

Traditional PID temperature control systems suffer from poor self-regulation and limited control performance. To address these limitations, researchers have combined PID control systems with intelligent algorithms, designing a fuzzy PID intelligent controller capable of handling both complex data and complex systems [3]. By leveraging the high flexibility of fuzzy control and the high

precision of PID control, this method effectively addresses challenges such as large system inertia and significant external disturbances in temperature control systems.

The basic process of fuzzy control involves three key steps: Fuzzification – converting input values into fuzzy variables, Fuzzy inference – applying predefined fuzzy logic rules to process the data, Defuzzification – converting the fuzzy results back into precise control values.

By integrating fuzzy theory into the PID control process, the system enables intelligent tuning of K_p , K_i , and K_d , enhancing its adaptability and control precision.

This design is based on the STC89C52 microcontroller as the main control core and integrates a fuzzy PID controller for temperature regulation. The DS18B20 temperature sensor, known for its comprehensive functionality, is selected for temperature measurement. The microcontroller (MCU) controls the relay switch, enabling the heating pad to operate and reach the preset temperature, while the LCD1620 displays the measured temperature.

This temperature control system is suitable for applications requiring high-speed response and precision temperature control. Compared to other PID-based temperature control systems, it offers higher temperature sensitivity and faster response speed.

The temperature acquisition circuit utilizes a Pt1000 resistance temperature detector (RTD) as the temperature sensor. The circuit converts the monitored actual temperature into a voltage signal, which is then transmitted to the MCU. The TLP521-1 optocoupler, in conjunction with a BD237 power transistor, drives the TEC module in the FTA951 system. The TEC (Thermoelectric Cooler) is regulated by a pulse-width modulation (PWM) signal generated by the MCU. The system dynamically adjusts PWM parameters based on the temperature difference between the measured temperature and the preset value. A host computer communicates with the system via a serial port, allowing users to input preset temperatures and monitor system operation status.

Experimental results indicate that this temperature control system features: Simple structure, Fast response speed, High stability and High temperature control accuracy. Temperature plays a critical role in industrial production and scientific research. Inaccurate temperature control can degrade measurement accuracy and system performance. In modern instrumentation, maintaining a stable temperature is crucial, such as in LED light sources, where precise temperature control ensures accurate lifetime prediction and photo-thermal characteristics analysis. For instance, the fiber optic gyroscope (FOG) is highly sensitive to temperature fluctuations. Even minor temperature variations can cause zero-drift errors, necessitating precise temperature control or compensation mechanisms. Practical applications demonstrate the need for further research into fast and high-precision temperature control systems.

3.2. Optimized FTA951 System

Typically, temperature control systems must support three operational modes: heating, cooling, and temperature stabilization. As shown in Figure 3, this study employs the FTA951 heating and cooling module as the temperature control actuator.

In cooling mode, the TEC in the FTA951 module actively reduces the temperature. In heating mode, the TEC operates with reverse current, allowing it to rapidly increase the sample stage temperature. The FTA951 module is designed with shock resistance, ensuring stable operation. The TEC's flat sample stage securely holds test samples. A fan-cooled heat sink is mounted on the TEC's opposite side to enhance heating efficiency. The sample stage is constructed from high thermal conductivity copper, ensuring efficient heat transfer.

The sample holder features two probe holes:

Probe T1: Near the surface of the sample stage, providing real-time feedback on actual temperature.

Probe T2: Located closer to the TEC, monitoring the reference temperature to determine thermal stability of the sample container.

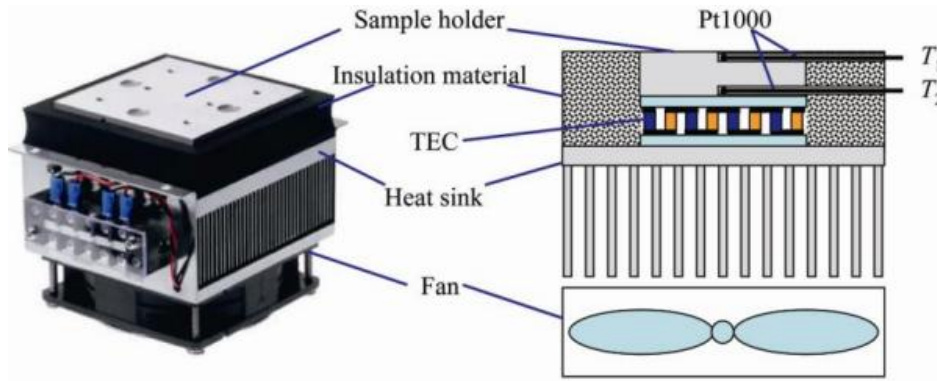


Figure 3. FTA951 system structure diagram [4]

To ensure that the actual temperature T_1 of the sample stage reaches the preset temperature T_0 quickly without significant overshoot, the system adjusts the effective power of the TEC (Thermoelectric Cooler) based on the temperature difference. When the difference between T_1 and T_0 is large, the effective power of the TEC is high. As T_1 approaches T_0 , the effective power gradually decreases. Once T_1 reaches T_0 , the effective power is reduced to a level that maintains minimal temperature fluctuations, keeping T_1 close to T_0 for an extended period.

3.3. Optimized FTA951 System

The incremental PID temperature control system is a variant of the traditional PID temperature control system. In the formula, $\Delta u(k)$ represents the increment of the control variable, and the incremental PID directly uses this as the basis for gradual temperature control. The parameters are adjusted based on the response [5].

$$\Delta u(k) = k_p (e(k) - e(k-1)) + k_i e(k) + k_d (e(k) - 2e(k-1) + e(k-2)) \quad (1)$$

The incremental PID control algorithm can be derived from formula (1). The output value of the controller at the $k-1$ sampling time can be obtained as follows:

$$u_{k-1} = k_p \left[e_{k-1} + \frac{T}{T_i} \sum_{j=0}^{k-1} e_j + T_d \frac{e_{k-1} - e_{k-2}}{T} \right] \quad (2)$$

By subtracting the first equation from the second and simplifying, a new algorithm formula for the incremental PID control system is derived. The calculation process is as follows [6]:

$$\begin{aligned} \Delta u_k &= u_k - u_{k-1} \\ &= k_p \left[e_k - e_{k-1} + \frac{T}{T_i} e_k + T_d \frac{e_k - 2e_{k-1} + e_{k-2}}{T} \right] \\ &= k_p \left(1 + \frac{T}{T_i} + \frac{T_d}{T} \right) e_k - k_p \left(1 + \frac{2T_d}{T} \right) e_{k-1} + k_p \frac{T_d}{T} e_{k-2} \\ &= A e_k - B e_{k-1} + C e_{k-2} \\ A &= k_p \left(1 + \frac{T}{T_i} + \frac{T_d}{T} \right), B = k_p \left(1 + \frac{2T_d}{T} \right), \\ C &= k_p \frac{T_d}{T} \end{aligned} \quad (3)$$

From formula (3), it can be seen that if the computer control system adopts a constant sampling period T , once A , B , and C are determined, the control amount can be derived using the deviation values from the previous three measurements, as shown in formula (3). The computational intensity

of the incremental PID control algorithm is much lower than that of the positional PID algorithm (1), which is why it is widely applied in practice. The core circuit diagram is shown in Figure 4 [7].

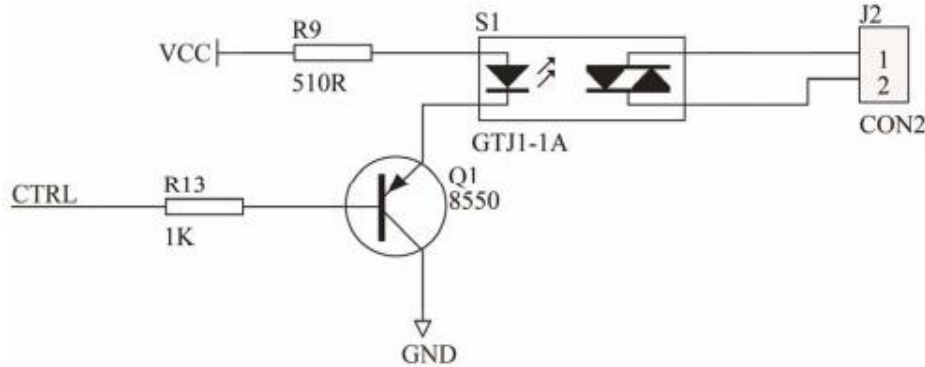


Figure 4. The core circuit diagram of the incremental PID temperature control system

If the traditional PID controller were directly applied to the control of the RF ablation temperature system, many challenges would arise, including overshoot, dependence on high-precision mathematical models, and difficulties in parameter adjustment. Therefore, to improve the effectiveness of RF ablation temperature control, a method combining an adaptive network-based fuzzy inference system (ANFIS) with the incremental PID controller is used to optimize the drawbacks of the PID controller in the RF ablation temperature controller [8]. The fuzzy inference system mentioned here represents a general direction for future PID temperature control systems, which will be elaborated on later with the fuzzy PID temperature control system.

Based on FPGA-in-the-loop simulation experiments and in-vitro experiments, the effectiveness of the ANFIS-PID controller in RF ablation temperature control was verified and compared with a PID controller under the same conditions. Experimental results show that, compared to the PID controller, the ANFIS-PID controller exhibits superior performance in terms of tracking capability and stability.

3.4. Radio Frequency (RF) Ablation System

In the defuzzification layer, T-type fuzzy inference is typically used to defuzzify the output of each rule (see formula (1)). To address the issue where the performance of a fixed parameter PID controller declines due to variations in the target temperature during the RFA (Radio Frequency Ablation) process, it is possible to use this type of incremental PID controller. Part of formula (1) is replaced by an incremental PID controller, and a new ANFIS-PID controller is constructed, as shown in formula (4) and (5) [9].

$$net_i = \overline{w_i} * (p_i * E + q_i * EC + ri) \quad (4)$$

$$net_i = \overline{w_i} * (k_p * EC + K_i * E + K_d * (E(k) - 2 * E(k-1) + E(k-2))) \quad (5)$$

This output corresponds to the third layer, where p_i , q_i , and ri are result parameters, with $i = 1, 2, 3, 4$, and E and EC are the inputs. This is its final expression. Figure 5 provides a schematic of the working structure of this type of PID temperature control system, the ANFIS-PID.

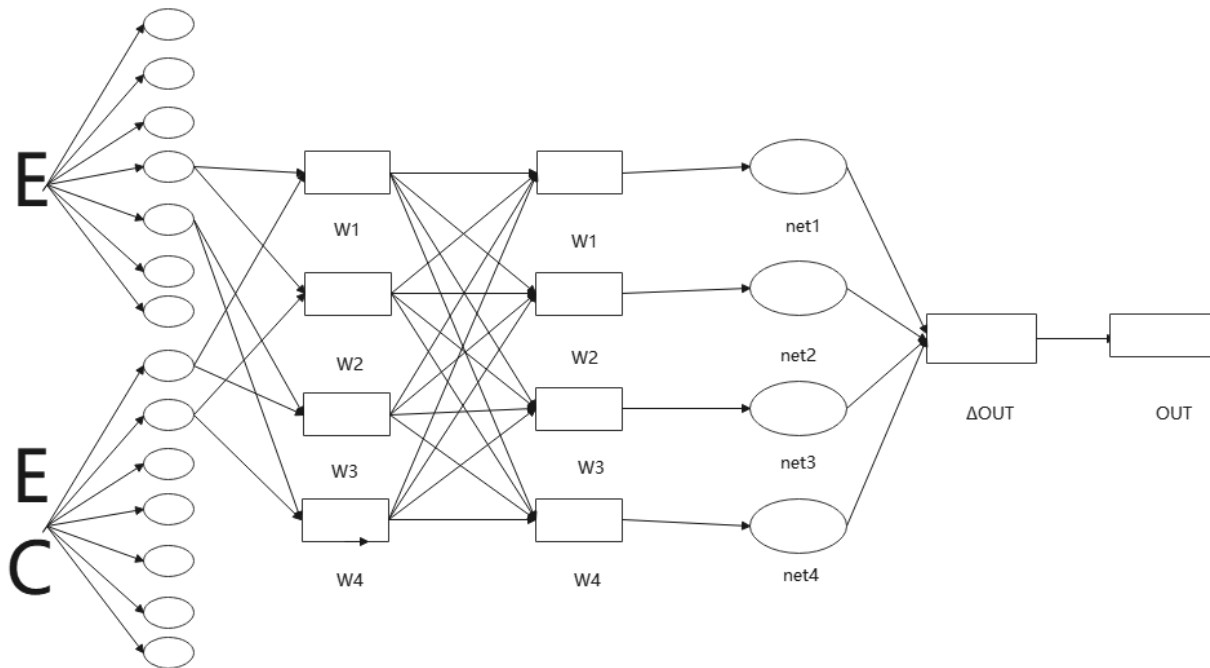


Figure 5. ANFIS-PID working diagram.

4. Conclusion

This paper has explored the optimization of PID (Proportional-Integral-Derivative) temperature control systems, particularly focusing on high-precision applications that demand fast response times, minimal overshoot, and high accuracy. Through the analysis of various PID control strategies and their adaptations to specific needs, such as the integration of fuzzy logic and incremental PID methods, significant improvements in control performance have been demonstrated.

One of the core contributions of this research is the development of a hybrid control system combining fuzzy inference with the PID algorithm, particularly for systems that require adaptive behavior in response to varying conditions, such as in Radio Frequency (RF) ablation or advanced thermal management systems. The inclusion of fuzzy logic has enhanced the flexibility and adaptability of the PID controller, allowing for dynamic adjustments to the system's parameters based on real-time temperature feedback. This hybrid approach has proven particularly beneficial in overcoming common challenges such as overshoot and sluggishness in conventional PID systems.

Moreover, the implementation of incremental PID control further optimized the system's computational efficiency. By reducing the calculation complexity compared to traditional PID algorithms, the system can achieve real-time adjustments without compromising performance, making it suitable for high-precision, time-sensitive applications. This approach, as demonstrated in the case of RF ablation systems, improves temperature regulation in environments where rapid temperature shifts are critical.

The experimental results presented in this paper confirm that the optimized PID control systems, especially those augmented with fuzzy logic and incremental PID methods, offer superior tracking capabilities, enhanced stability, and better overall temperature control precision compared to traditional PID systems. These findings underline the importance of developing adaptive control strategies for high-precision systems where even minor temperature deviations can lead to significant performance degradation.

In summary, this research not only presents a refined PID control strategy for temperature regulation in high-precision environments but also highlights the potential of hybrid and adaptive control systems to address the limitations of conventional PID controllers. Future work will explore further optimizations, such as the integration of machine learning techniques to improve system response and the ability to predict and mitigate temperature fluctuations in real-time. Additionally,

further investigation into the practical applications of these optimized control strategies in diverse fields, such as semiconductor manufacturing, medical devices, and aerospace systems, could open new pathways for advanced, high-precision temperature control.

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