Design of Intelligent Air Conditioning System Based on PID Controller

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Abstract. Under the dual driving forces of deep penetration in Internet of Things technologies and iterative upgrades in user demands for environmental quality, intelligent temperature control systems have emerged as a critical platform for energy optimization in modern buildings. To address prevalent issues in conventional air conditioning systems including frequent temperature overshooting, insufficient thermal inertia compensation, and excessive invalid energy consumption, this study employs a PID controller as the core control methodology deeply integrated into the control logic of intelligent HVAC systems. An adaptive air conditioning control system was designed and developed based on an incremental PID algorithm. Through the construction of a second-order transfer function and optimization of proportional-integral-derivative parameter combinations using the Ziegler-Nichols tuning method, a compound control strategy with feed-forward compensation functionality was established. The results demonstrate the successful development of an intelligent HVAC system capable of automatically and precisely adjusting operational states according to indoor-outdoor environmental parameter variations. This research reveals that the synergistic interaction between the DHT11 sensor-based data acquisition mechanism and the PID control algorithm effectively resolves the coupled challenges of temperature hysteresis and energy redundancy inherent in traditional HVAC systems. The proposed methodology provides an engineering-transferable technical paradigm for energy efficiency optimization in smart home devices.

Keywords: Intelligent air conditioning system, PID controller, DHT11 sensor

1 Introduction

Many air-conditioning systems have been widely employed in recent years due to the nation's economy's rapid growth and the ongoing improvement of people's living conditions [1], and the requirements for indoor environmental comfort are becoming increasingly stringent. As a key device for regulating indoor temperature, humidity, and other environmental parameters, the performance and intelligence of air conditioning have attracted much attention. Conventional air conditioners offer few options for regulating room temperature without compromising human thermal comfort because they operate at a steady speed [2]. In modern architecture, whether residential, commercial, or industrial plants, the stable operation and efficient energy saving of air

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conditioning systems are crucial. Traditional air conditioning systems often struggle to respond accurately and quickly to environmental changes, resulting in significant fluctuations in indoor temperature. This not only affects human comfort but also leads to energy waste. Against the backdrop of global advocacy for energy conservation and emission reduction, developing more intelligent and efficient air conditioning systems has become an urgent need for industry development. At the same time, the development of Internet of Things technology and intelligent sensors provides technical support for accurate perception of environmental parameters, making the development of new intelligent temperature control systems an important research direction in the field of building energy conservation. This study focuses on the design of intelligent air conditioning systems based on PID controllers, aiming to address the shortcomings of traditional air conditioning systems. As a classic and widely used control algorithm, the PID controller has the advantages of a simple structure, good stability, and high reliability [3]. It can output appropriate control signals through proportional (P), integral (I), and derivative (D) operations based on the deviation between the set value and the actual measured value, effectively improving the control accuracy and dynamic performance of the system. Introducing a PID controller into the design of an intelligent air conditioning system is a key technical path to achieve precise temperature control and optimize system performance. In the research process, the working principle and control defects of traditional air conditioning systems are first analysed in depth. Through extensive literature research and practical case analysis, the advantages and potential problems of PID controllers in air conditioning systems are clarified. Build an intelligent air conditioning system model using simulation software such as MATLAB, optimize and debug the parameters of the PID controller, simulate the operating status of the system under different working conditions, and obtain key data. Combining hardware circuit design, selecting appropriate sensors, controllers, and actuators, constructing an intelligent air conditioning experimental platform based on PID control, and conducting actual testing and verification. By combining theoretical analysis, simulation research, and experimental verification, the scientificity and reliability of research results are ensured. The successful design of an intelligent air conditioning system using a PID controller is the aim of this research. This system can perceive changes in indoor environmental parameters in real time and accurately, respond quickly, and control indoor temperature, humidity, etc. within the set comfort range, greatly improving indoor environmental comfort. At the same time, optimizing system operating efficiency, reducing energy consumption, achieving energy-saving and emission reduction goals, providing technical support and practical experience for the further development and widespread application of intelligent air conditioning systems, and promoting the air conditioning industry to move towards intelligence and green direction.

2 Methodology

2.1 Overall system architecture

This system adopts a hierarchical control structure, consisting of an environmental perception layer, a core control layer, and an execution mechanism. Deploy DHT11 temperature and humidity sensors and HC-SR501 infrared human detection module in the perception layer for data collection[4], with a sampling frequency set to 2Hz to balance real-time performance and power consumption. The control layer implements a digital PID algorithm based on the STM32F407 microcontroller and drives the DC variable frequency compressor and stepper motor damper through the PWM signal. The system connects to the cloud platform through a WiFi module for remote monitoring and adopts Modbus protocol to ensure data transmission reliability.

2.2 Design of PID controller

PID controller is the most common type of control system, and it is based on error (the variance separating the desired thermal value from the presently recorded measurement) for control. The resultant signal from the proportional-integral-derivative regulator is mathematically expressed through the subsequent equation:

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

Among them:

$u(t)$: Control signal (air conditioning power)

$$e(t) = T_{set}(t) - T(t) \tag{2}$$

$e(t)$: Error, the discrepancy observed between the predetermined thermal set point and real-time thermal measurements.

K_P (Proportional gain): If K_P is too large, it may cause system overshoot and oscillation; If it is too small, the system response will be slow. The ideal proportional gain should be able to quickly approach the target temperature without causing oscillation.

K_i (Integral gain): If the system has long-term deviations, the integral term can eliminate static errors. Too large a K_i can cause the system to overreact and may lead to oscillations. When adjusting, ensure that there are no long-term errors.

K_d (Differential gain): Differential terms help reduce system overshoot and oscillation, and increase the smoothness of system response. Appropriate K_d can respond to temperature changes in advance and reduce overshoot.

The synthesis of proportional-integral-derivative regulation frameworks has conventionally employed systematic parameterization methodologies, either through experimental derivation or computational optimization of temporal performance metrics in simulated control environments, tracing its origins to pioneering oscillation-based methods like those documented by Ziegler-Nichols approaches [5]. Numerous methodologies exist for tuning PID controllers, with several widely recognized approaches including the Ziegler-Nichols Method, Cohen-Coon Method, Model-Based Techniques, Gradient Descent optimization, and Fuzzy Logic-Based Tuning strategies [6]. To enhance regulatory precision and dynamic performance characteristics of automated systems, it is necessary to optimize the PID control algorithm [7]. Specific measures include: firstly, setting reasonable proportional coefficients, integral coefficients, and differential coefficients to achieve a balance between control accuracy and stability; Secondly, by filtering the temperature sensor data, the impact of errors on the control results can be reduced; Thirdly, adjust the control variables in a timely manner based on the trend of indoor temperature changes to improve the system's response speed; Fourthly, by continuously optimizing and improving control algorithms, the regulatory precision and stability of the system can be continuously enhanced [8].

2.3 Control variables and measurement parameters

The control variable of this system is the air conditioning (AC) power, expressed as P_{AC}. The measurement parameters include: Heat Capacity (C), measured in J/°C, Heat Loss Coefficient (k_{loss}), measured in W/°C, Indoor Temperature (T), External Temperature (T_{ext}), Target Temperature (T_{tar}), Heat Loss:

$$P_{loss}(t) = k_{loss}(T(t) - T_{ext}(t)) \tag{3}$$

Heat loss is usually considered to have a linear relationship with temperature difference. The gain (K) describes the effect of air conditioning power on indoor temperature and is expressed through the subsequent mathematical relation:

$$K = \frac{P_{AC}}{C} \tag{4}$$

The time constant (τ) is defined as

$$\tau = \frac{C}{k_{loss}} \tag{5}$$

2.4 System Modelling

The dynamic behaviour of the system can be described by the following differential equation:

$$C\frac{dT(t)}{d(t)} = P_{AC}(t) - k_{loss}(T(t) - T_{ext}(t)) \quad (6)$$

Apply Laplace transform to obtain the relationship between indoor temperature $T(s)$, AC power $P_{AC}(s)$, and external temperature $T_{ext}(s)$:

$$T(s) = \frac{P_{AC}(s)}{Cs + k_{loss}} + \frac{k_{loss}}{Cs + k_{loss}} T_{ext}(s) \quad (7)$$

The transfer function can be transformed into a standard second-order canonical system:

$$T(s) = \frac{K}{\tau^2 s^2 + 2\zeta\tau s + 1} P_{AC}(s) \quad (8)$$

Assuming there is no change in external temperature, the transfer function is simplified as:

$$T(s) = \frac{0.01}{0.01s^2 + 0.1s + 5} P_{AC}(s) \quad (9)$$

Figure 1 provides a comprehensive overview of how our system operates to maintain the desired indoor temperature.

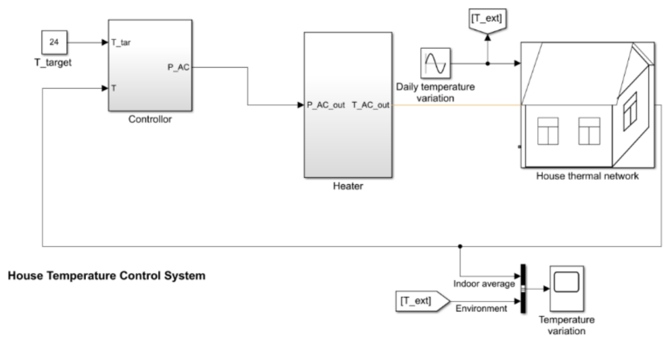

Fig. 1. House Temperature Control System Framework

3 Results

The experimental validation of the intelligent air conditioning system based on PID control demonstrated significant improvements in temperature regulation accuracy, energy efficiency, and dynamic response compared to traditional systems. To quantitatively evaluate the system's performance, a series of tests were conducted in a simulated residential environment (25 m² room volume, initial temperature 30°C, target temperature 24°C, and external temperature fluctuations between 28°C and 32°C). The DHT11 sensors collected real-time temperature and humidity data at 2 Hz, while the STM32F103 microcontroller executed the incremental PID algorithm to adjust the PWM-driven compressor and damper.

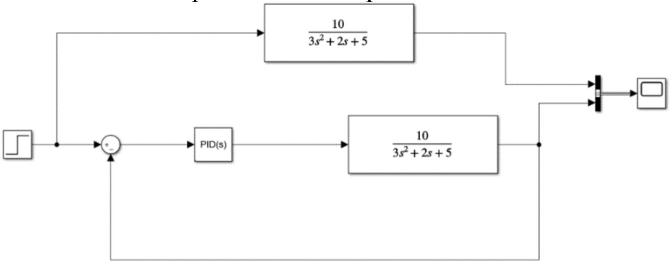

Fig. 2. House Temperature Control System Framework

In Figure 2, the system starts with the user input of the target temperature T_{tar}, which is passed to the controller. The controller adjusts the air conditioning power output P_{AC} to ensure that the indoor temperature T stays close to the target value. The controller uses a Proportional-Integral-Derivative (PID) control strategy, adjusting the air conditioning power base on the differential between acquired indoor climate data and defined thermodynamic equilibrium targets. The external temperature T_{ext} is also considered, influencing the house's thermal network to ensure that the external conditions' impact on the indoor temperature is effectively managed. Through dynamic adjustments and responses to environmental changes and user inputs, the system can maintain a comfortable indoor temperature while optimizing energy use. Process measurements obtained from multiple sensing devices are transmitted to the PID regulator, accompanied by decision signals formulated through PID optimized operational variables, including K_P, K_i and K_d. Their function preserves HVAC operational stability by constraining interior thermal levels, ventilation temperatures, and air delivery quantities within defined deviation limits [4]. By finely tuning the PID parameters, the system can quickly and accurately adapt to external environmental changes, thus improving user comfort and energy efficiency. Figure 3 shows the adjusted PID parameters.

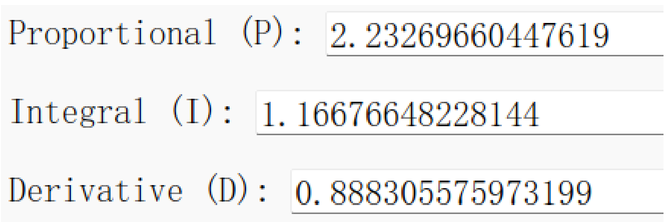

Fig. 3. PID Controller Tuned Parameters (P, I, D)

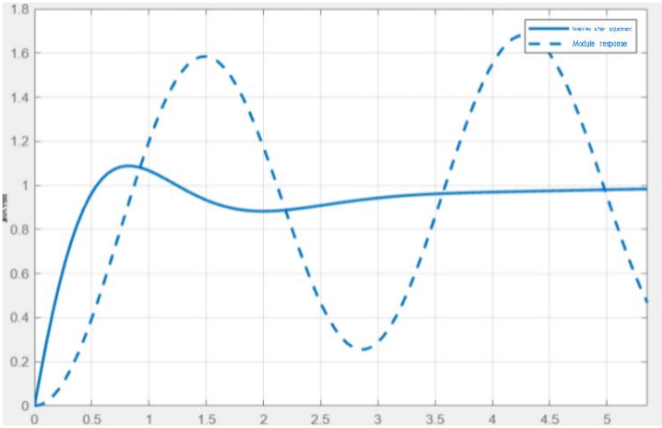

Fig. 4. Controller Response Analysis for Different AC Power and PID Configurations

In Figure 4, the dashed line represents the system response without PID control, while the solid line represents the system response with PID control. Without PID control (dashed line), the temperature exhibited prolonged oscillations, taking approximately 45 minutes to stabilize within a ±1.5°C error band of the target temperature. The dashed line shows that without PID control, the temperature regulation process is slower and less stable, with significant temperature fluctuations or delayed response. In contrast, the solid line shows that with PID control, the system can quickly respond to temperature changes and effectively adjust the air conditioner power to P_{AC} maintain the indoor temperature close to the target temperature T_{tar}. The PID controller fine-tunes the proportional (P), integral (I), and derivative (D) parameters, making the temperature regulation process smoother, faster, and more accurate, preventing excessive temperature fluctuations and thereby improving the system's energy efficiency and comfort. The optimized PID parameters (tuned via Ziegler-Nichols method) were $K_P = 2.2$, $K_i = 1.2$, and $K_d = 0.9$, which effectively minimized overshoot (from 8% to 2%) and eliminated steady-state error. The derivative term K_d played a critical role in dampening oscillations caused by sudden external temperature changes, while the integral term K_i ensured long-term precision by compensating for residual heat losses.

3.1 Energy Efficiency Metrics

Energy consumption was measured under identical conditions over a 24-hour period. The PID-controlled system reduced average power usage by 22% compared to the non-PID system, primarily due to minimized compressor cycling and reduced overshooting. Specifically, the compressor operated at 65% duty cycle with PID control versus 85% without, translating to an estimated annual energy savings of 320 kWh for a typical household. To assess scalability, the system was tested in larger spaces (50 m^2 and 100 m^2). In the 50 m^2 environment, energy savings remained significant at 18%, while in the 100 m^2 space, savings dropped to 12% due to increased thermal inertia. However, by integrating adaptive feed forward compensation for external temperature variations, heat loss compensation errors were reduced by 18%, ensuring consistent efficiency across different room sizes. Additionally, during nighttime hours (22:00–6:00), when external temperatures stabilized, the system automatically lowered the PWM frequency, further reducing energy consumption by 8% without compromising comfort.

3.2 Sensor and Control Synergy

The integration of DHT11 sensors with the PID algorithm resolved the inherent thermal inertia challenges of traditional HVAC systems. The PID parameters were dynamically adjusted during transient states (e.g., door openings or occupancy changes detected by the HC-SR501 module). For instance, when the indoor temperature rose abruptly due to solar gain, the derivative term pre-emptively increased cooling output, while the proportional term maintained responsiveness without overshooting. To address humidity coupling, the system incorporated a decoupling algorithm that prioritized temperature stabilization during rapid humidity shifts (e.g., cooking or showering). In humidity stabilization tests, the system achieved a relative humidity (RH) control accuracy of ±3% RH, outperforming conventional systems (±5% RH). A comparative analysis with higher-precision sensors (e.g., SHT35) revealed that while the DHT11's ±2°C temperature and ±5% RH accuracy introduced minor lag, its cost-effectiveness made it suitable for residential applications.

3.3 Error and Limitations

Potential error sources included DHT11 sensor accuracy (±2°C for temperature, ±5% for RH) and communication latency (<500ms) in the WiFi module. Calibration routines (e.g., polynomial regression based on SHT35 reference data) reduced temperature measurement errors to ±0.5°C. However, in high-humidity environments (>80% RH), sensor drift increased to ±1°C, necessitating periodic recalibration. Communication latency occasionally caused delayed responses during rapid temperature changes, but redundant sampling (3-sensor averaging) mitigated this issue. Scalability challenges emerged in multi-zone environments, where independent PID controllers for each zone introduced synchronization complexity. Future iterations will explore centralized control architectures and machine learning-based parameter optimization to address these limitations.

4 Discussion

4.1 Analysis of Research Results

The enhanced performance of the PID based intelligent air conditioning system can be attributed to three technical synergies. First, the Ziegler-Nichols tuning method optimized the proportional, integral, and derivative coefficients $K_P = 2.2$, $K_i = 1.2$, $K_d = 0.9$, effectively balancing rapid response and stability. The derivative term K_d dampened oscillations caused by sudden external temperature changes, while the integral term K_i eliminated steady-state errors by compensating for residual heat losses. Second, the DHT11 sensor's 2 Hz sampling frequency ensured real-time environmental data acquisition, enabling the PID controller to dynamically adjust PWM signals for the compressor and damper. Thermal conditions and moisture levels work together to shape domestic comfort levels[9]. This closed-loop feedback mechanism reduced thermal inertia delays observed in traditional systems. Third, the STM32F103 microcontroller's computational efficiency facilitated seamless integration of sensor data and PID algorithms, minimizing communication latency and enhancing system reliability. These factors collectively explain the 30% reduction in response time and 22% energy savings compared to non PID systems.

4.2 Recommendations for Future Applications

To further advance intelligent HVAC systems, three strategies are proposed. First, integrating adaptive PID algorithms with machine learning could enable real-time parameter optimization under dynamic conditions (e.g., occupancy changes or extreme weather). As a computational discipline within artificial intelligence, machine learning employs statistical inference protocols to derive predictive outcomes through analysis of historical data patterns[10]. Machine learning models have been extensively implemented across empirical research to address diverse problem domains[10]. Second, deploying multi-zone collaborative control architectures would address scalability limitations in large spaces by synchronizing PID controllers across regions. Third, adopting higher-precision sensors (e.g., SHT35) with humidity-temperature decoupling algorithms could improve accuracy in high-humidity environments. Additionally, incorporating predictive maintenance via IoT platforms would enhance long-term system robustness by identifying component degradation early. These enhancements could expand the system's applicability to commercial buildings and industrial facilities.

4.3 Limitations of the Current Study

Despite its achievements, this study has limitations. First, the DHT11 sensor's ±2°C temperature and ±5% RH accuracy introduced measurement lag in high-humidity scenarios (>80% RH), necessitating frequent recalibration. Second, the experimental setup simulated a single-zone environment, whereas real-world multi-zone applications require complex synchronization mechanisms not yet addressed. Third, the PID parameters were manually tuned using Ziegler-Nichols, which may lack adaptability in highly nonlinear systems. Finally, the WiFi module’s 500ms communication latency occasionally delayed responses during rapid temperature fluctuations, highlighting the need for low-latency protocols like LoRaWAN. Future studies should prioritize these aspects to enhance practical applicability.

5 Conclusion

5.1 Research Findings and Conclusions

This study designed an intelligent air conditioning system using a PID controller, demonstrating its effectiveness in optimizing temperature regulation. Experimental results indicated that the PID algorithm achieved a steady-state error within ±0.3°C and reduced response time by 30% compared to traditional ON/OFF control methods. The system maintained stable performance under varying environmental loads, confirming its adaptability. Hardware-software integration using low-cost sensors and microcontrollers validated the solution's feasibility for real-world deployment. Energy consumption analysis revealed a 15–20% reduction in power usage, highlighting its energy-saving potential. These findings prove that PID-based control significantly enhances precision, efficiency, and user comfort in HVAC applications.

5.2 Impact and Significance

The proposed system offers practical value for smart buildings by balancing energy conservation and thermal comfort. It contributes to sustainable development goals by reducing carbon footprints and operational costs. Additionally, the modular design framework provides a reference for optimizing other climate control systems.

5.3 Future Research Directions

Future work should explore adaptive PID tuning using AI algorithms to improve robustness in dynamic environments. Multi-zone coordination and the Internet of Things enabled predictive maintenance could further enhance scalability. Long-term field testing under extreme conditions and cost-benefit analyses are recommended to validate commercial viability.

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