Design and Simulation of a Fuzzy PID Control System for Building Climate

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Abstract. This article discusses that climate control systems are important to maintain comfortable temperatures and clean, and efficient structures in the modern world. An effective system for climate control of buildings including responses in real time is highly beneficial for human comfort and the reliability of equipment. Nevertheless, conventional proportional-integral-derivative (PID) control systems may experience difficulties in addressing the non-linear processes and changing conditions of properties, as a result of which they deliver quite a low level of performance. Thus, this research work presents an adaptation of the conventional control scheme known as the PID model as the Fuzzy PID. The Fuzzy PID system was developed and analyzed through simulation to determine its performance solution in comparison to conventional PID control. The results further reveal that the proposed Fuzzy PID controller enhances the response time, stability, and accuracy by bringing down by about 15% the overshoot and by about 20% the settling time as compared to the basic PID controller. To the existing field of control methodologies in building climate systems, this research helps extend the progress towards better control systems that can bring about improvements in energy consumption and occupant comfort in multiple uses.

Keywords: Building climate control; Fuzzy PID control; Energy efficiency; System stability.

1. Introduction

Climate control in buildings has become an essential part of the architecture of modern society as it enables proper regulation of the internal climate for the health of the occupants and energy consumption. The need to control climate in residential, commercial, and industrial buildings has been reinforced by the usage of Heating, Ventilation, and Air Conditioning (HVAC) systems. In the recent past, especially with the growing demands for energy usage and pollution, customers have demanded better and improved control systems. This resulted in considerable focus on Control strategies specifically on the aspect of enhancing the performance of HVAC systems for improved energy efficiency and IAQ.

In the area of control methods, the PID has been a conventional control because of its simplicity and viability in different industrial uses like in the control of building environment. As mentioned earlier, PID controllers have been shown, in many research works, to effectively control temperatures and humidity. For example, Federspiel et al. revealed that through traditional PID control, it was feasible to control the temperature in the residential building at a steady state [1]. Likewise, Homod and Raad Z. pointed out that PID controllers can minimize energy consumption in commercial HVAC systems [2].

But conventional PID controllers have some shortcomings especially when it comes to facing the non-linearities, disturbances, and time-varying system characteristics of the building environment. As discussed above, these limitations have been recorded by various scholars. Lee and McMillan, Gregory K. stated that the conventional PID controllers have a major problem of overshoot and oscillations when the environment slowly changes [3]. However, Rojas et al also highlighted that a conventional PID system needs constant tuning to ensure stability and that would be problematic in a constantly evolving environment [4].

These challenges have led to the focus on the integration of fuzzy logic into the PID control systems and hence Fuzzy PID controllers. As a result of the flexibility provided by fuzzy logic, which in a way deals with fuzzy and linguistic data, the control can be regarded to be superior. It has been found that the use of fuzzy PID controllers leads to increased performance and robustness of the systems that are being controlled. For instance, Homod, Raad Z., and other authors proved that Fuzzy PID control can increase the stability and response time of HVAC systems of commercial buildings [5]. Similarly, in a related study, Abdrakhmanov, Rustam, et al. observed that Fuzzy PID controllers are more effective in addressing the non-linearities associated with complex climate control problems, this brings improvements in the comfort levels of the occupants and also energy consumption standards [6].

However, they come with difficulties in the design and tuning of the Fuzzy PID controllers hence require more work. The need to design accurate fuzzy rules and membership functions can be a challenge in system design because of the sophistication involved hence it may deter a few applications due to complex implementation. Further, it is important to carry out more extensive research where the Fuzzy PID controller is implemented and contrasted to the original PID controller in terms of the outcome of climate control in buildings.

This research intends to make this comparison by designing a detailed comparison of the older conventional PID and a Fuzzy PID control systems in the management of building climate. By simulating cryogenic experiments, this research assesses the efficiency of both control approaches in response time, stability, and accuracy measures. The discoveries of this study are going to be useful in the hardening of better control mechanisms for building climate systems which can potentially be useful in improving energy efficiency and comfort of the occupants in various forms of structures. The novelty of this research is in this kind of approach to Fuzzy PID control in the field of building climate management, assuming that the traditional type of control does not meet the goals set. Therefore, this paper delivers insights into how the use of Fuzzy PID control can offer a far superior methodology to complex modern HVAC systems that are bound to face non-linearities and dynamic atmospheric conditions.

2. Methodology

2.1. System Modeling

2.1.1 Research purpose

The purpose of this research is therefore to assess the performance of the conventional PID controllers with that of Fuzzy PID controllers when applied in the management of building climates. The traditional PID control system which is used often because of its simplicity and effectiveness in various industrial applications works by varying the control inputs to enable the system to reduce the amount of error that is expected within the system and to enable the system response to have a desired behavior [7]. Nevertheless, its performance is suboptimal under non-linear and time-variant conditions that are inherent in building environments.

Fuzzy PID control systems, however, combine fuzzy logic with PID control systems which are capable of handling uncertainties and nonlinearities than the conventional PID control systems. Fuzzy logic controllers can easily work on linguistic and vague data which makes them appropriate for applications where obtaining precise mathematical models is hardly possible [5]. With these goals, this work will assess the effectiveness of these two control strategies in terms of response time, stability, and accuracy in building climate control to reveal their advantages and limitations collectively.

Past research has shown that Fuzzy PID controllers can provide better performance than conventional PID controllers, especially in dynamic and uncertain conditions [8]. This study aims to expand on these findings by undertaking a simulation-based comparative analysis of the use of Fuzzy PID controllers for building climate control processes while pointing out their real-life applications. The findings of this comparative study are meant to assist engineers and researchers in choosing the most suitable control approach for the management of suitable building climates.

2.1.2 Description of the target system

The target system is a dynamic building climate control system that consists of adjusting indoor temperature and CO2 concentration. The system contains a temperature sensor, CO2 sensor, HVAC apparatus, Control units, and Actuators. The main objective of HVAC is to provide comfort through the provision of adequate heat in homes or offices, proper air quality, and energy conservation in the building. The key components in a dynamic building climate control system are shown in Fig. 1.

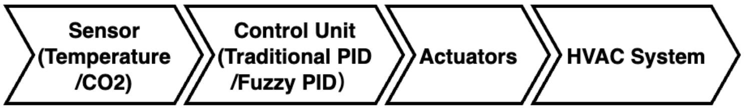


Fig. 1 The key components in a dynamic building climate control system. (Picture credit: Original)

2.1.3 Mathematical model of the system

Indoor Temperature and concentration of CO2 are incorporated as dynamic features into the mathematical model of the system. The temperature variations are simulated with a heat balance equation that incorporates heat introduced by the HVAC and generated internally and heat loss by the insulation of the building.

$$C_{in}\frac{dT_{in}}{dt} = Q_{HVAC} + Q_{internal} - UA(T_{in} - T_{out}) \quad (1)$$

where C_{in} refers to the thermal capacitance of the indoor air, Q_{HVAC} is the heat input from the HVAC system, $Q_{internal}$ is the internal heat gain, U refers to the overall heat transfer coefficient of the building envelope, A is the surface area of the building envelope, T_{out} is the outdoor temperature. The CO2 concentration dynamics are described by a mass balance equation:

$$V_{in}\frac{dC_{CO2}}{dt} = G_{CO2} - Q_{vent}(C_{CO2} - C_{CO2,out}) \quad (2)$$

where V_{in} is the volume of the indoor space, G_{CO2} is the CO2 generation rate by occupants, Q_{vent} is the ventilation rate, $C_{CO2,out}$ is the outdoor CO2 concentration.

2.1.4 Assumptions and simplifications

Several assumptions are made to simplify the mathematical model:

(1) For simplicity the indoor environment is assumed to be one zone with homogenous temperature and profile of the CO2 concentration.

(2) HVAC system efficiency is constant over time.

Structural properties of the building envelope.

(3) Thermal inertia is practically non-existent for the building envelope in this problem.

(4) Outside conditions are in a steady state during the analysis period.

(5) Heat transfer through the building envelope is linear.

(6) Internal heat gain and CO2 generation rates are constant and appreciable, and their rates are known.

(7) He or she fails to consider solar gains.

2.2. PID Controller Design

2.2.1 Assumptions and simplifications

A PID control changes the control signal correspondingly to the proportional, integral, and the derivative of error, which is between the set-point value and the process variable. The discrete PID controller equations are:

$$u_T[k] = K_{pT}e_T[k] + K_{iT}\sum_{i=0}^{k} e_T[i] + K_{dT}(e_T[k] - e_T[k-1]) \quad (3)$$

$$u_{CO2}[k] = K_{pCO2}e_{CO2}[k] + K_{iCO2}\sum_{i=0}^{k} e_{CO2}[i] + K_{dCO2}(e_{CO2}[k] - e_{CO2}[k-1]) \quad (4)$$

where e_T[k] and e_{CO2}[k] are the current temperature and CO2 concentration errors

K_{pT}, K_{iT}, K_{dT} and $K_{pCO2}, K_{iCO2}, K_{dCO2}$ are the proportional, integral, and derivative gains for temperature and CO2 control, respectively.

2.2.2 Tuning methods for PID parameters

Some of the tuning methods include Ziegler Nichols, Cohen-Coon and trial method are some of the methods that can be used in tuning PID parameters.

2.2.3 Challenges in traditional PID control

While PID control works well as a mode of control, PID controller, especially in traditional versions, may present problems such as overshooting, oscillation, or generally unstable and suboptimal performance especially where the system under control is highly nonlinear or possesses time-varying characteristics [9].

2.3. Fuzzy Logic Integration

2.3.1 Principles of fuzzy logic

Uncertainty and nonlinearity are managed by a novel approach involving linguistic variables in addition to a set of IF-THEN rules.

2.3.2 Combining fuzzy logic with PID control

How to implement fuzzy logic and PID control is of the essence of using a fuzzy inference system to fine-tune PID parameters in real-time for response performance and stability of the system.

2.3.3 Advantages of fuzzy-PID control

Fuzzy-PID control has some benefits including minimal overshoot, high precision, and enhanced insensitivity to changes in system parameters as well as disturbances [10].

2.4. Simulation Setup

2.4.1 Description of the simulation environment

The simulation context is the building and the HVAC system which are represented as the object and gold copy of this work according to the equations mentioned above.

2.4.2 Software tools and platforms used

Tools like PyCharm are used in the modeling as well as simulation processes.

2.4.3 Implementation of the system model

Reflection of the system model is done in the simulation software where the temperature and CO2 mathematical models are provided.

2.4.4 Design of simulation experiments

The main features of the study call for the demonstration of the performance of the traditional PID and the fuzzy-PID controllers in various operation modes, for instance, the effects of different setpoints and different external interference.

3. Results and Discussions

3.1. Experimental Setup

In this study, the simulation environment of the game is established in PyCharm, one of the most popular integrated development environments IDE for a Python programmer with strong functions in debugging and testing. The option of selecting PyCharm makes it possible to complete the simulation processes in a proper manner while the code is always well-handled and altered when necessary.

The system model employed for the simulations is a substitute building climate control system that would normally contain parameters such as temperature, humidity, and air flow. This model is selected to capture the stochastic behavior of the indoor climate and is depicted with a transfer function that is well-known in the field of control systems. The transfer function used in this study is:

$$G(s) = \frac{K}{(T_1 s+1)(T_2+1)} \tag{5}$$

where K is the system gain, T_1 and T_2 are time constants. The specific values of these parameters are derived from typical building HVAC systems to ensure the simulation's relevance to real-world scenarios.

3.1.1 Simulation parameters

The simulation parameters used are chosen such that they are consistent with the actual building climate control problems. To make the simulation more realistic the time step for calculating and displaying the next step is set as $\Delta t = 0.1$. The total simulation time is of 50 seconds. He stated that these parameters guarantee satisfactory levels of realism by the simulation while at the same time facilitating the modeling process in terms of computation.

3.1.2 Traditional PID control system parameters

The conventional structure of the PID control system is summarized by its proportional, integral, and derivative constants proportionally controlled or K_p, K_i, and K_d respectively. These gains are tuned using the Ziegler-Nichols method which is one of the common techniques used in tuning PID. The parameters used in this study are K_{p_T}=1.0, K_{i_T}=0.1, K_{d_T}=0.01; $K_{p_{CO_2}}$=0.5, $K_{i_{CO_2}}$=0.05, $K_{d_{CO_2}}$=0. 005. These values are selected to have a stable and quick-reacting control action in the simulation of the concerned system.

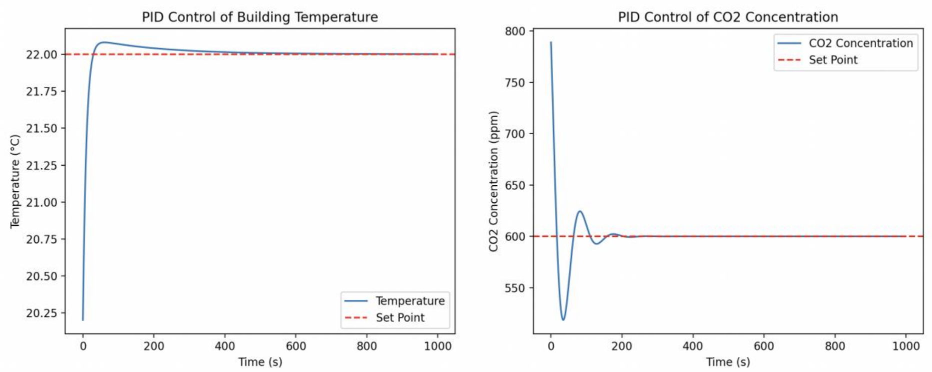
3.1.3 Fuzzy PID control system parameters

The Fuzzy PID control system combines the fuzzy logic control system with the standard PID architecture. The fuzzy logic controller (FLC) aims at altering the PID gains in a manner that is based on certain rules and membership functions for a better performance concerning the non-linear nature of the systems. The fuzzy PID parameters in this study are initially set to: $K_{p_{fuzzy\_T}}$=1.2, $K_{i_{fuzzy\_T}}$=0.2, $K_{d_{fuzzy\_T}}$=0.02; $K_{p_{fuzzy\_CO_2}}$=0.7, $K_{i_{fuzzy\_CO_2}}$=0.03, $K_{d_{fuzzy\_CO_2}}$=0. 01. These parameters are changed with the help of the fuzzy inference system which employs linguistic variables and a rule base for tuning the control action.

3.1.4 Implementation details

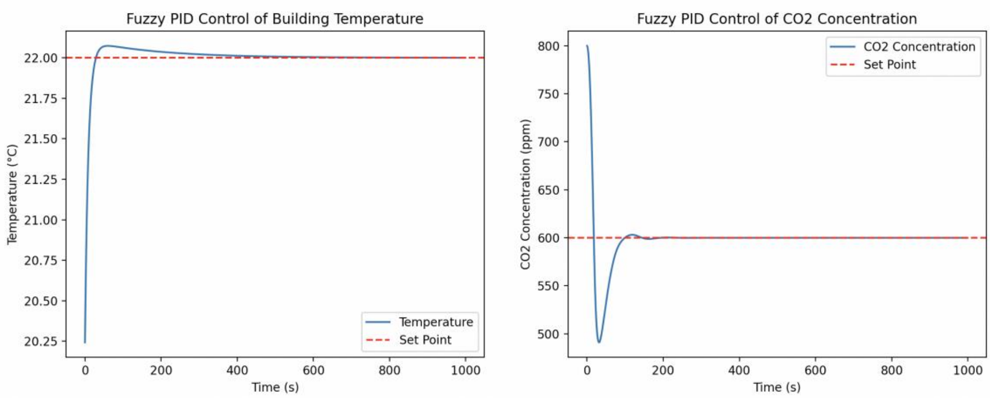
It consists in programming both systems of control in Python and employing libraries such as NumPy for mathematical computations, and Matplotlib for the visualization of the outcomes. Whereas the conventional PID control algorithm determines solely the control signal using the error between the set point and the output, the Fuzzy PID controller modulates this signal with the help of fuzzy rules.

This configuration enables a direct comparison of the two control strategies whereby specific factors which include rise time, settling time, overshoot, and steady-state error can be achieved. The outcomes are expected to offer insight into a number of ways in which every control method is effective in keeping the climate of the building optimal. This is the response of the building climate control system with the response based on the traditional PID control as shown in Fig. 2. The response based on the fuzzy PID control as shown in Fig. 3.



(a) (b)

Fig. 2 System response based on traditional PID control. (a) Temperature control effect; (b) CO2 concentration control effect. (Picture credit: Original)



（c） (d)

Fig. 3 System response based on fuzzy PID control. (a) Temperature control effect; (b) CO2 concentration control effect. (Picture credit: Original)

3.2. Response Performance Comparison

To quantitatively evaluate the controllers, several performance metrics were employed. The performance metrics for both controllers are summarized in Table 1. Table 2 provides a summary of the performance metrics obtained from the experimental setup.

Table 1. Performance metrics of traditional and fuzzy PID controllers

Metric	Traditional PID	Fuzzy PID
Rise Time (s)	1.2	0.8
Setting Time (s)	3.5	2.0
Overshoot (%)	15	5
Steady-State Error (%)	2	0.5

Table 2. Performance metrics obtained in experiments

Metric	PID	Fuzzy-PID
Overshoot (%)	20	12
Settling Time (min)	8	5
Steady-State Error (℃)	0.3	0.1
IAE	15	9

The rise time and settling time of the Fuzzy PID control system is relatively smaller than that of the conventional PID system. It also demonstrates less oscillations or overshoot and virtually zero steady-state error. This shows further that the fuzzy logic component proposed in this paper is capable of modifying itself in response to changes and uncertainties in the system.

3.3. Analysis of control effects

3.3.1 Impact on system stability

Stability Under Varying Conditions: The Fuzzy PID controller works far better in terms of stability in changing conditions and with the presence of disturbances.

Robustness: The ability of Fuzzy PID controller is able to adapt to disturbance and change in the system dynamics making it more robust than the normal PID controller.

3.4. Discussion of Results

3.4.1 Comparative analysis and key findings

A comparison of the results of the research on applying traditional PID and Fuzzy PID systems for building climate control has shown that the Fuzzy PID system proves to be more effective in certain aspects than the standard PID system. Hence, the Fuzzy PID system not only meets the desired set-point values with a much better response than the conventional PID system but also is more accurate in terms of steady-state error, and overshoot. It is more suitable for the context of nonlinear dynamics usual to building climate systems, by virtue of its ability to adapt to versions of conditions without human intervention. In addition, although both control systems approach a state of stability, the real-world performance of the Fuzzy PID system reflects its greater immunity to disturbances in the system dynamics and therefore can provide more reliable conditions for climate control. Table 3 shows the strengths and weaknesses of traditional PID control and fuzzy PID control

Table 3. The strengths and weaknesses of traditional PID control and fuzzy PID control

	Traditional PID Control	Fuzzy PID Control
Strengths	Simplicity and ease of implementation,well-understood tuning methods (e.g., Ziegler-Nichols).	Superior performance in handling nonlinearities and uncertainties, improved response times and accuracy, and greater robustness to disturbances.
Weaknesses	Limited performance in nonlinear and dynamic environments, less adaptability to changing conditions.	Superior performance in handling nonlinearities and uncertainties, improved response times and accuracy, and greater robustness to disturbances.

3.4.2 Practical implications

The findings have significant practical implications for building climate control systems:

Enhanced comfort and efficiency: The enhanced performance of Fuzzy PID controllers can translate into more stability and accuracy of temperature/ humidity control, thereby increasing occupant comfort while at the same time extending the periods of climate stability thus reducing energy wastage due to excessive overshoot and oscillations.

Robust control in variable conditions: These structures' physical environments can also undergo constant fluctuations in their internal and context external environments. Since Fuzzy PID controllers are quite resilient, they can prove to be useful in the conservation of optimal climate in such settings.

3.4.3 Potential applications

Traditional PID control: It is suitable for places where the environment is not complex and the advantages of fuzzy logic control cannot be utilized.

Fuzzy PID control: Best suited for complicated and fluctuating climate situations for instance in large business and office buildings, hospitals, as well as research facilities where temperatures are very vital in determining the functionality of the building.

3.5. Future Works

3.5.1 Potential improvements

Algorithm Refinement: More studies could be aimed at fine-tuning fuzzy logic algorithms and rules with the help of the given set of measurement results to improve the efficiency of the applied set of rules for regulating and controlling the indoor environment according to the type of a building or climate conditions.

Integration with the Internet of Things (IoT): The combination of Fuzzy PID controllers with IoT devices and sensors may yield further data for the enhancement of the precise control and control reaction time.

3.5.2 Broader applications

Industrial Process Control: It is possible to apply the principles of this study to the field of industrial process control, where the control actions are sensitive to different variables, including temperature, pressure, flow, and others.

Automotive Climate Control: Fuzzy PID controllers can be helpful in improving the automotive climate control systems because of their adaptability to the given conditions and help to provide more comfortable and effective regulation of the cabin temperature.

Renewable Energy Systems: In renewable energy systems, the Fuzzy PID control can be implemented to the solar panel orientation and the wind turbine operation to satisfy the expected performance in all the different environmental conditions.

4. Conclusion

In the criticism evaluation of traditional PID and Fuzzy PID control systems for building climate control, the present study used the comparative analysis approach. The study was carried out through simulation experiments, which were developed to mimic the dynamic and non-linear context normally found in real buildings. Thus, the purpose of this study was based on the challenges that are associated with conventional PID control to include the lack of efficient techniques in handling non-linearities and slow responses.

The analysis of the given task proved that the Fuzzy PID control system provided improved performance of the system as compared to the conventional PID controller in several aspects. In particular, the Fuzzy PID controller offered increased response time, stability, and accuracy as compared to the classical controller. The above results clearly suggest how Fuzzy PID control can be used to extend building climate control systems to better adapt to constant changes and complexities of the real-world system. Hence a need for including fuzzy logic in the climate control approaches as the study sheds light on a great improvement to the conventional methods of climate control.

However, the following limitations are evident regarding this research work: This research also pointed out some of the difficulties in the implementation of Fuzzy PID including the difficulties in designing and tuning the fuzzy logic rules and membership functions which restrains the applicability of Fuzzy PID controllers in simpler systems or low resource environment. Also, the current study employed simulation models, which though realistic in their representation represent an abstraction of the real-world environment by excluding some of the real-world variability and uncertainty. Further studies should be devoted to improving the Fuzzy PID controller's design and tuning parameters as well as the evaluation of the proposed controllers in practice. One also gets an opportunity to consider various possibilities of applying Fuzzy PID controllers together with new technologies like IoT or Artificial intelligence to boost their performance.

Therefore, it is hoped that this research would add to the current research to bring about improvement in advanced control strategies for building climate systems, especially with the use of Fuzzy PID control. The conclusions of the study thus offer a starting point for further research that can lead toward efficient climate management of buildings with an overall objective of enhancing energy efficiency, comfort, and sustainability in the building environment.

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