

Enhanced Control Mechanisms in Autonomous Systems: Integrating Fuzzy Logic with PID Controllers

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Abstract. The integration of Fuzzy Logic with Proportional-Integral-Derivative (PID) controllers in autonomous systems presents a significant advancement in control mechanisms, offering both adaptability and robustness. This paper delves into the key advantages of this hybrid approach, providing a thorough analysis of its implementation. Fuzzy Logic enhances the conventional PID controller by introducing a layer of reasoning that mimics human decision-making, allowing for better handling of uncertainties and nonlinearities in the system. Several common applications of fuzzy control are discussed, demonstrating its versatility in various domains such as robotics, automotive systems, and industrial automation. The integration of Fuzzy Logic with PID controllers is particularly beneficial in environments where precise control is required despite the presence of dynamic and unpredictable conditions. This hybrid approach ensures smoother transitions, reduced overshoot, and improved stability, making it ideal for complex autonomous systems. The paper provides a detailed explanation of how Fuzzy Logic complements the traditional PID framework, enhancing its performance and flexibility. By adjusting the PID parameters in real-time based on fuzzy rules, the controller can adapt to changing conditions more effectively, leading to superior control performance. This comprehensive analysis underscores the potential of integrating Fuzzy Logic with PID controllers, paving the way for more intelligent and responsive autonomous systems.

Keywords: Fuzzy logic, PID, control.

1. Introduction

This essay examines the integration of fuzzy logic with PID controllers in autonomous systems. Fuzzy logic is a mathematical tool designed to handle imprecise and vague information by mapping input variables to output variables through the definition of fuzzy sets and fuzzy rules. In control systems, fuzzy logic is particularly useful for managing nonlinear and complex systems, especially those that are difficult to describe with precise mathematical models. The PID controller, a widely used control algorithm, adjusts the control signal based on the error between the system's input and output. It consists of three components: Proportional (P), Integral (I), and Derivative (D). By adjusting the parameters of these three components, different control effects can be achieved.

- Integrating fuzzy logic with PID controllers enhances control mechanisms in several ways. The advantages of this integration include:

- Improved Robustness: Fuzzy logic can handle system uncertainties and vagueness. When combined with PID controllers, it enhances the robustness of the entire control system, making it more adaptable to complex and changing environments [1].

- Optimized Control Performance: Through the rule adjustment of fuzzy logic, the parameters of the PID controller can be dynamically adjusted, optimizing control performance and improving the system's response speed and stability.

Simplified Parameter Adjustment: Adjusting the parameters of traditional PID controllers requires certain experience and skills. However, the combination of fuzzy logic and PID controllers simplifies the parameter adjustment process through fuzzy rules, reducing the difficulty of adjustment [2]. The implementation steps for integrating fuzzy logic with PID controllers are as follows: First, establish a fuzzy inference system by defining fuzzy sets and fuzzy rules for the inputs and outputs. Next, design the PID controller by setting the proportional, integral, and derivative gains and adjusting the PID parameters to achieve the desired control performance. Finally, combine the fuzzy inference

system with the PID controller, using the output of the fuzzy inference system as the input for the PID controller, thereby realizing the integration of fuzzy logic and PID control.

In conclusion, the integration of fuzzy logic and PID controllers offers enhanced control mechanisms, improving the control performance and robustness of autonomous systems. This integration method has unique advantages in handling complex and uncertain control systems.

2. Relevant Theories

2.1. Development History of fuzzy PID

The Birth of Fuzzy Control Theory (1965): In 1965, American scientist L.A. Zadeh published a seminal paper on "Fuzzy Sets" in the journal "Information and Control," marking the inception of fuzzy set theory and laying the groundwork for subsequent research and applications in fuzzy control theory [3]. **Early Development of Fuzzy Control (1965-1974):** This period primarily focused on the development and formation of fuzzy mathematics. Zadeh continued to advance fuzzy set theory, proposing fuzzy algorithms and fuzzy logic reasoning methods. In 1974, Dr. Mamdani of the University of London successfully developed the world's first fuzzy-controlled steam engine, marking the transition of fuzzy control from theoretical research to practical applications [4].

Maturation of Fuzzy Control Technology (1974-1979): During this period, simple fuzzy controllers began to emerge. Fuzzy control was applied in various control systems, such as cement dryers. Although fuzzy control demonstrated its advantages, its adaptive capability and robustness were limited, and steady-state accuracy was not ideal [5]. **Development of High-Performance Fuzzy Control (1979-Present):** In 1979, T.J. Procky and E.H. Mamdani jointly proposed the concept of self-learning, significantly enhancing the performance of fuzzy control systems. Since then, fuzzy control has entered a stage of high-performance development. It has been widely applied in various complex control systems, including subways, water treatment, and temperature control. For example, in 1987, the Sendai subway line in Japan adopted a fuzzy logic controller, and in 1989, Japan introduced fuzzy logic consumer products to the market, marking the widespread adoption of fuzzy control technology in practical applications [6]. **The Emergence of Fuzzy PID Controllers:** With the maturity of fuzzy control technology and the extensive use of PID controllers, researchers began to explore the combination of both to form fuzzy PID controllers. These controllers merge the simplicity and robustness of PID controllers with the intelligence of fuzzy control, enabling better adaptation to complex control problems such as nonlinearity and time-varying uncertainties. Fuzzy PID controllers adjust PID parameters through fuzzy rules to achieve real-time control and have been applied in various fields, including the injection molding industry, gyroscope temperature control, and cotton topping manipulator control [7].

2.2. Principle of fuzzy Logic

2.2.1. What is fuzzy logic

Fuzzy logic is a way to model logical reasoning, where the truth of a statement is not a binary, true or false, like it is with classical logic, but rather it's a degree of truth that ranges from zero, which is absolutely false, to one which is absolutely true. fuzzy logic allows people to design a fuzzy inference system, which is a function that maps a set of inputs to outputs using human interpretable rules rather than more abstract mathematics. As is shown in Figure 1 below [8].



Fig. 1 Structural diagram (Photo credit: Original).

The fuzzy relation obtained by the fuzzy condition is shown in formula (1).

$$R_i = A_i \times B_i \times C_i \quad (1)$$

A combination of Mandeni's fuzzy reasoning is shown in formula (2).

$$C_i = (A_i \times B_i) \circ R_i \quad (2)$$

The control aspect of the robot can be transformed into a quadratic transfer function as shown in Formula (3).

$$G(s) = \frac{K}{T_1 s^2 + T_2 s + 1} \quad (3)$$

These types of functions are popular for control applications, where a reference and measurements are fed in and then using a set of rules based on fuzzy logic, some actuating signal is produced. But fuzzy logic is larger than just a control technique as it can be used for any decision-making process. As is shown in Figure 2 below [9].



Fig. 2 Diagrams (Photo credit: Original).

2.2.2. How fuzzy logic works

If give a precise input into the fuzzification, it will get through the inference engine and defuzzification and get a precise output finally. Maybe it is abstract and not easy to understand, so an example will be given to explain it. As is shown in Figure 3 below.

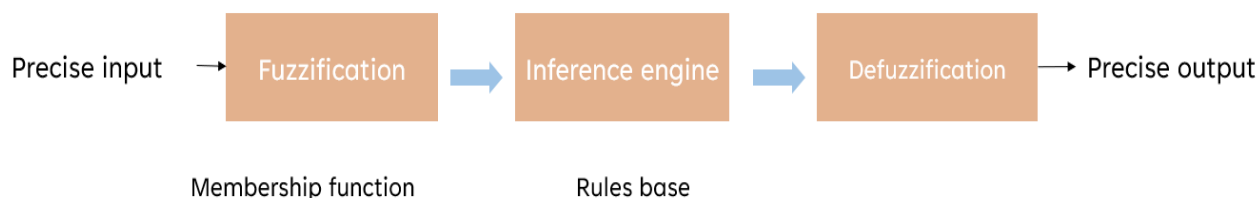


Fig. 3 Flow chart (Photo credit: Original).

Now just imagine someone wants to apply a loan from the bank, in this problem, the bankers will look at his credit rating and try to determine the risk, the banker might take advantage of existing knowledge and experience in the form of rules. For example, a rule might be if a person has good credit, then the applicant is deemed low risk. If they have neutral credit, then they are medium risk and bad credit, then they are high risk [10]. So, in this way, the rules themselves that have been developed over time based on experience and data are the encoding of knowledge. They are the model that can be used for prediction, in this case the prediction of whether a person will pay back a loan or not. So, if someone wants to come up with a function that can assess risk automatically, it would make sense to base it on the existing knowledge that is baked into the set of rules that people have

already developed rather than try to develop a mathematical model of something as complex as human finance. As is shown in Figure 4 below.

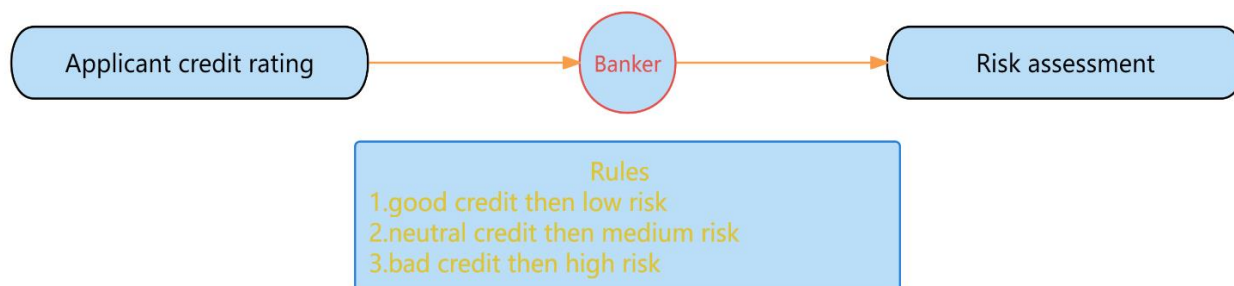


Fig. 4 Flow chart (Photo credit: Original).

3. System Analysis and Application Research

3.1. Temperature Control System

From metallurgy, furnaces, grain silos, to greenhouse farming, biopharmaceuticals, and chemical engineering, the real-time monitoring and control of temperature are directly linked to the quality and performance of products. However, due to the inherent characteristics of temperature systems, such as hysteresis, large inertia, and nonlinearity, achieving precise control poses a certain degree of difficulty. To address this, researchers have developed various temperature control strategies. Among them, the PID algorithm has gained widespread application in industrial temperature control due to its simple control method and remarkable effect. The PID controller effectively controls the system by adjusting three parameters: proportion, integration, and differentiation, reducing temperature deviations and enhancing the stability and response speed of the system. As is shown in Figure 5 below.

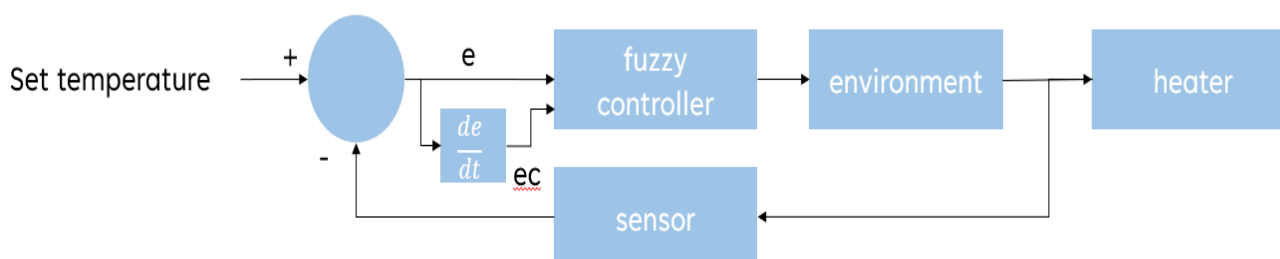


Fig. 5 Diagram (Photo credit: Original).

With technological advancements, intelligent temperature control systems are beginning to integrate more advanced features, such as adaptive adjustment, fuzzy logic control, and neural networks. For instance, the variable universe fuzzy PID control method enhances the adaptability and accuracy of the control system by dynamically adjusting control parameters. Additionally, some systems incorporate single-chip technology to achieve intelligent temperature control, enabling real-time temperature measurement, parameter setting, voice alerts, remote control, and other intelligent functions.

In practical applications, the design of temperature control systems requires consideration of numerous factors, including control accuracy, system stability, operational convenience, and cost-effectiveness. For example, the STM32-based self-tuning PID temperature control system for mixing mills effectively resolves the issue of single-polarity adjustment of electric valves through an improved relay feedback PID algorithm, enhancing the system's robustness and control accuracy.

In summary, temperature control systems are evolving towards greater intelligence and automation. Systems integrated with advanced control algorithms and intelligent technologies not only provide higher control accuracy and stability but also meet specific temperature control requirements in different application scenarios. Future research will continue to explore more efficient, reliable, and

economical temperature control solutions to accommodate the ever-changing industrial and daily needs.

3.2. Greenhouse Control

In recent years, with the development of precision agriculture and intelligent greenhouse technology, greenhouse temperature control has become an important research field. Temperature control is crucial for maintaining crop growth and increasing yield. However, due to the complexity and variability of the greenhouse environment, achieving precise temperature control poses certain challenges. Traditionally, PID controllers have been widely used in greenhouse temperature control due to their simple structure and high stability. Nevertheless, faced with the large lag, non-linearity, and time-varying characteristics of the greenhouse system, the effect of standard PID control is not ideal, especially in parameter tuning, which is difficult to adapt to changes in system characteristics. As is shown in Figure 6 below.



Fig. 6 Example 1 (Photo credit: Original).

Fuzzy control has gained attention due to its ability to handle uncertainty and fuzziness, but it lacks in steady-state accuracy. Neural network control possesses strong nonlinear approximation capabilities and self-learning abilities, but it requires significant computational resources and is sensitive to initial parameters. In these studies, literature proposed a greenhouse temperature control technology based on an improved BP neural network PID controller. This technology optimizes PID controller parameters through neural network self-learning and weight coefficient adjustment, and utilizes the particle swarm optimization algorithm to enhance the learning efficiency of the neural network, effectively overcoming the limitations of traditional BP algorithms.

Literature designed an intelligent measurement and control system for greenhouses based on a segmented control strategy. This system combines PID algorithms and fuzzy control theory, adjusting greenhouse control equipment through real-time monitoring and intelligent decision-making output to create optimal growth conditions. Literature explored the design of a fuzzy PID intelligent irrigation controller and verified its effectiveness through MATLAB simulations. This controller adjusts PID controller parameters through fuzzy control, improving the system's dynamic response speed and adaptability.

Literature studied greenhouse environmental optimization control based on improved multi-objective evolutionary algorithms. This method achieves precise control of the greenhouse environment by optimizing PID controller parameters. Literature designed a BP neural network PID controller and conducted simulation studies. The results show that this controller has stronger adaptability and robustness, and its control quality is superior to conventional PID controllers.

In summary, combining intelligent control algorithms with PID control can not only improve the accuracy and adaptability of greenhouse temperature control but also enhance the system's robustness. These research achievements provide new solutions for greenhouse temperature control, which is significant for promoting the development of intelligent agriculture. Future research can further explore more efficient and precise control strategies and how to apply these strategies to actual greenhouse control systems.

3.3. Traffic Lights Control

In recent years, research in the field of traffic light control has primarily focused on optimizing traffic flow, reducing congestion, and improving road usage efficiency through advanced technologies and algorithms. In traffic light control, PID controllers can be used to adjust the timing of signal lights in response to real-time changes in traffic flow. For example, by adjusting the Proportional (P), Integral (I), and Derivative (D) parameters of the PID controller, the green light duration can be optimized, reducing vehicle waiting time and enhancing the intersection's traffic efficiency. However, traditional PID controllers may have limitations in handling complex and nonlinear traffic systems as they are often based on linear control theory.

As a crucial component of urban traffic management, the core objective of traffic light control is to ensure smooth traffic flow and safety. Traditional traffic light control methods often rely on fixed schedules or real-time data from vehicle detectors to adjust signal cycles. However, with the development of Connected Vehicle (CV) technology, adaptive signal control methods based on vehicle communication have demonstrated significant advantages. As is shown in Figure 7 below.



Fig. 7 Example diagram 2 (Photo credit: Original).

Fuzzy Logic Controllers (FLC) provide a powerful tool to handle uncertainty and fuzziness, particularly suitable for complex systems that are difficult to describe with traditional mathematical models. In traffic light control, fuzzy logic can be used to handle the uncertainty and variability of traffic flow. The application of fuzzy logic in traffic and parking management mentioned in literature demonstrates how fuzzy logic can optimize the allocation of parking spaces and the management of traffic flow. FLC processes inputs (such as vehicle arrival rates, number of waiting vehicles) and outputs (such as green light duration) by defining a set of fuzzy rules, thus achieving intelligent control of traffic light signals.

Although literature primarily focuses on the issue of handover authentication in 5G heterogeneous networks, the proposed fuzzy logic-based model is also applicable to scenarios requiring multi-criteria decision-making, such as traffic light control. Through fuzzy logic, multiple factors can be comprehensively considered, and the timing of traffic lights can be dynamically adjusted based on the fuzzy sets of these factors.

In summary, research in traffic light control is heading towards the integration of more intelligent technologies, such as connected vehicles, edge computing, fuzzy logic, and multi-criteria decision-making models. The application of these technologies can not only improve the efficiency and adaptability of traffic light control systems but also provide drivers with a safer and smoother traffic experience. Future research will continue to explore how to utilize these advanced technologies to address increasingly complex urban traffic challenges.

3.4. Path Planning

In the field of autonomous driving and intelligent transportation systems, path planning is a crucial technical challenge that involves effectively guiding vehicles from their starting points to destinations. Recent advancements in PID controllers and fuzzy logic controllers have significantly improved path planning techniques. However, due to system lags and random disturbances in path planning, traditional PID algorithms may fail to meet the requirements for high precision and strong adaptability. To address this issue, researchers have proposed path planning methods based on improved Fuzzy-PID control theory. In document, a novel Fuzzy-PID composite control system is introduced, which realizes the weighted combination of PID and fuzzy control outputs through a switching switch under fuzzy rules, fully utilizing the advantages of both. This method adjusts the parameters of the fuzzy membership function to obtain the optimal control scheme for the system, thus improving the performance of path planning. Fuzzy logic controllers have also been widely used in path planning due to their strong adaptability, flexible control, and independence from object models. Document proposes a fuzzy adaptive PID control-based navigation control system for unmanned aerial vehicles (UAVs). This system establishes a fuzzy control rule table based on expert experience and the practical applications of micro-UAVs, and utilizes the maximum anti-fuzzification rule to obtain specific PID control parameters. Actual flights have shown that compared to traditional PID control algorithms, fuzzy PID controllers exhibit better performance in terms of adjustment time and accuracy. Document investigates the fuzzy PID synchronous control of the tether line system for tethered UAVs. A fuzzy PID-based control system is designed to address the latency issues of the tether line. Simulation results demonstrate that the fuzzy PID control system has advantages such as small overshoot, better stability, and faster response speed, meeting the requirements for synchronous operation between the tethered UAV system and the UAV. In document, a fuzzy PID correction algorithm based on optimal deviation paths is proposed to address the trajectory tracking issue of vision-guided automatic guided vehicles (AGVs) using QR codes as positioning modules. This method first establishes the kinematic equation of the AGV, then introduces the Hamilton optimal control function to obtain the optimal deviation path and optimal control equation for the AGV based on the optimal deviation conversion strategy. Finally, the parameters of the fuzzy PID controller are updated based on the pose deviation between the AGV and the optimal deviation path, achieving optimal control for AGV correction. Document explores the application of Matlab in Fuzzy-PID controllers for ship maneuvering simulations. The study designs a fuzzy controller that can perform fuzzy calculations and fuzzy reasoning in real-time, implementing Fuzzy-PID control for ship maneuvering controllers. Tests show that the controller exhibits excellent dynamic response performance and steady-state control accuracy, thereby improving maneuvering performance and enhancing the robustness of the controller. In summary, the applications of PID and fuzzy logic controllers in path planning demonstrate their tremendous potential in improving system performance, adaptability, and stability. Future research can further explore the performance of these controllers in more complex traffic environments and path planning for different types of vehicles, as well as how to integrate them with other intelligent transportation system components to achieve more efficient and safer urban traffic management.

4. Challenges

The integration of Fuzzy Logic with PID Controllers in Enhanced Control Mechanisms for Autonomous Systems poses several challenges. Here are some key challenges in a structured format.

Complexity of Design and Implementation: designing a fuzzy PID controller involves the creation of a fuzzy inference system, which requires defining fuzzy sets, membership functions, and fuzzy rules. This adds complexity compared to traditional PID controllers. Implementing the fuzzy PID controller in a real-world autonomous system requires careful integration with the system's hardware and software.

Tuning and Optimization: tuning the parameters of a fuzzy PID controller is a complex task, as it involves optimizing both the fuzzy rules and the PID gains (KP, KI, KD). This is often done through trial-and-error or advanced optimization techniques.

Achieving the desired performance characteristics, such as response speed, stability, and accuracy, can be challenging due to the interactions between the fuzzy and PID components.

Real-time Performance: autonomous systems require controllers that can respond quickly and accurately in real-time. The fuzzy PID controller must be able to perform the necessary computations within the required time constraints. The computational complexity of the fuzzy inference system can impact the real-time performance of the controller.

Robustness and Adaptability: autonomous systems operate in dynamic and uncertain environments. The fuzzy PID controller must be robust to noise, disturbances, and changes in the system's parameters. The fuzzy rules and PID gains may need to be adapted online to maintain optimal performance under changing conditions.

Integration with Other System Components: the fuzzy PID controller must be integrated with other system components, such as sensors, actuators, and communication interfaces. This requires careful coordination and synchronization. Ensuring compatibility and interoperability with different system components can be a challenge.

5. Conclusion

The integration of fuzzy logic with Proportional-Integral-Derivative (PID) controllers in autonomous systems signifies a substantial advancement in control mechanisms. This hybrid approach merges the traditional precision and reliability of PID controllers with the flexibility and adaptability of fuzzy logic systems, resulting in a more robust and efficient control strategy. PID controllers have long been the backbone of industrial automation, providing stable and predictable control across a broad spectrum of systems. However, they often face challenges when dealing with complex, nonlinear, or uncertain environments. This is where fuzzy logic excels.

Fuzzy logic is a form of computing that manages imprecise and uncertain information, enabling more flexible and adaptive control strategies. It effectively handles complex systems that are difficult to model mathematically and can adjust its behavior based on the system's current state.

By integrating fuzzy logic with PID controllers, several benefits are achieved. Firstly, the fuzzy logic component can introduce a "fuzzy" correction term to the PID output, allowing for finer adjustments to the system. This mitigates the effects of noise, disturbances, and other uncertainties in the environment. Secondly, fuzzy logic can dynamically adjust the PID parameters (such as the proportional, integral, and derivative gains) based on the system's current state. This adaptive capability enables the controller to optimize its performance in response to changing conditions. Finally, combining fuzzy logic and PID controllers enhances the overall system's robustness and fault tolerance. Even if certain components fail or behave unexpectedly, the fuzzy logic component can compensate for these issues, maintaining stability and performance.

In summary, the integration of fuzzy logic with PID controllers represents a promising approach for enhancing control mechanisms in autonomous systems. It combines the precision and reliability of PID controllers with the flexibility and adaptability of fuzzy logic, resulting in a more robust and efficient control strategy capable of managing complex, nonlinear, and uncertain environments..

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