Research on Signal Stability of Mobile Robots Based on Fuzzy PID Control

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Abstract. The study of signal stability in mobile robots has been a crucial research topic. It represents one of the essential parameters for assessing system operational reliability. Proportional-Integral-Derivative (PID) control is widely applied in mobile robot control technology. However, in nonlinear systems with strong disturbances, precise algorithm models are required, and pure fuzzy control exhibits steady-state errors. Therefore, the fuzzy PID method is proposed, combining the flexibility and adaptability of fuzzy control to achieve higher control precision and stability. This paper reviews research on mobile robot signal stability based on fuzzy PID control, elaborating on fuzzy PID control principles, its applications in mobile robots, and signal stability analysis to optimize mobile robot control systems. Meanwhile, this research can provide feasible control solutions for mobile robot design in practical applications. The paper aims to provide theoretical foundations for improving mobile robot signal stability, conduct in-depth discussions of previous research, understand current research status and development trends, and offer valuable assistance for future development.

Keywords: Mobile Robot; Fuzzy PID Control; Signal Stability; Improved Particle Swarm Algorithm.

1. Introduction

In modern society, mobile robots have significantly impacted human life, gradually replacing humans in various aspects. They are not only applied in industrial fields, such as unmanned handling, cutting, and welding robots, but their influence extends to daily life, including navigation, medical care, and food industries. Mobile robots can independently complete various tasks with stable, continuous, and efficient operation, improving production efficiency and reducing labor costs. Robots employ multiple sensors, control systems, and positioning systems, making them safer, more flexible, and more accurate than manual operations [1]. Research on signal stability is crucial for robot movement, navigation, and task execution capabilities, serving as a key factor in maintaining stable system output signals and measuring system performance. If robots lack stability during movement, their reliability decreases and accidents become more likely, making this a constant focus of researchers. Motion control technology plays an important role in mobile robotics, enabling real-time control of robot movement position, state, and trajectory. As information and control technology develop toward intelligence, Proportional-Integral-Derivative (PID) control, as a core control technology, is widely used due to its simple structure and strong reliability. However, in practical applications where robots operate in complex, disturbed, and nonlinear environments, traditional control cannot establish accurate mathematical models, thus failing to achieve satisfactory control effects. Fuzzy PID control offers greater flexibility, real-time adjustment capability, and more convenient parameter tuning compared to traditional PID control [2]. Pure fuzzy controllers lack integral action and cannot eliminate steady-state errors. Therefore, combining fuzzy control with PID control helps improve mobile robot stability, control precision, and robustness, while also addressing the long response time defect of conventional PID control, achieving ideal results [3]. Melo AG et al. proposed a PID controller based on fuzzy gain scheduling for AUV trajectory tracking [4]. Hasan MW et al. proposed an adaptive fuzzy nonlinear PID controller to address unknown uncertainties and ocean current disturbances in underwater robotic vehicles [5]. Kumar A demonstrated that IT2-FPID controllers outperform traditional controllers in disturbed, coupled, and highly complex nonlinear situations [6]. This indicates that fuzzy PID is suitable for applications like trajectory tracking, and improved fuzzy PID controllers perform better in terms of performance and stability in uncertain, highly disturbed environments.

This paper reviews and analyzes the current status and development trends of mobile robot signal stability research based on fuzzy PID control technology, summarizes fuzzy PID principles, discusses its applications in mobile robots, compares the advantages and disadvantages of this research, proposes improvement suggestions, and provides future directions.

2. Fuzzy PID Control Principles

2.1. Traditional PID Control

PID control measures the error between the actual output and desired output of the control system, performs calculations using three parameters - Proportional (P), Integral (I), and Derivative (D) - to obtain control quantities and adjust system input to make output approach the desired value as closely as possible.

Proportional Control (P): This is the simplest control method. The controller output has a proportional relationship with the input error signal, enabling quick error response but unable to eliminate steady-state errors.

Integral Control (I): Building upon proportional control, integral terms are added to create a proportional relationship between controller output and the integral of input error signals. Integral adjustment eliminates steady-state errors but slows system response.

Derivative Control (D): The controller output has a proportional relationship with the derivative of the input error signal (i.e., error change rate), predicting error change trends and thus producing feed-forward control action to avoid overshoot phenomena and improve system dynamic performance. The calculation formula is:

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

where K_p, K_i, K_d are the gains for proportional, integral, and derivative terms respectively.

2.2. Fuzzy PID Control Principles

Fuzzy PID control builds upon traditional PID control by using fuzzy logic and specific fuzzy rules to dynamically adjust the three PID controller parameters to meet system requirements under different conditions, addressing traditional PID's shortcomings and improving overall system control effects. This method effectively reduces overshoot and oscillation while maintaining system response speed, thereby improving system stability and precision. Fuzzy PID control takes error value e and e_c error change rate as inputs, PID's three parameters (K_p, K_i, K_d) as outputs, sequentially completing fuzzification, establishing fuzzy rules, obtaining fuzzy relationships, then performing fuzzy logic reasoning and defuzzification. Most importantly, it identifies fuzzy relationships between the three PID parameters and error and error change rate, continuously monitoring e and e_c , and adjusting parameters to meet e and e_c requirements for PID parameter self-tuning under different conditions.

The fuzzy PID control system structure is shown in Fig. 1 [7]. When mobile robots operate in nonlinear or uncertain environments, the fuzzy PID control system needs real-time adjustment to ensure normal robot operation. System input is the wheel speed set by the controller, and the final value is the digital feedback from the photoelectric encoder [8]. The new adjustment values for the three original PID parameters after system correction are ΔK_p , $\Delta K_i, \Delta K_d$, and adding initial values gives the final parameters, as shown in the following formulas:

$$Kp = K'p + \Delta Kp \tag{2}$$

$$Ki = K'i + \Delta Ki \tag{3}$$

$$Kd = K'_d + \Delta Kd \tag{4}$$

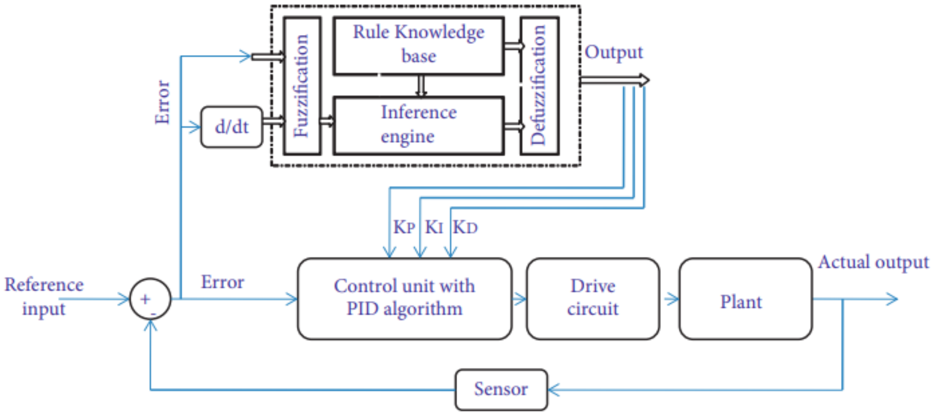

Fig. 1 Fuzzy PID Control Structure Diagram [7]

3. Applications of Fuzzy PID Control in Mobile Robots

Path Tracking: Through fuzzy PID control algorithms, parameters are adaptively adjusted based on real-time system status and input signals, with control signals ultimately output to robot actuators to achieve path tracking control. Through experimental analysis and continuous optimization, tracking performance is enhanced for precise following of predetermined paths. For example, self-correcting nonlinear fuzzy PID controllers applied to multi-input multi-output (MIMO) fully actuated autonomous underwater vehicles can follow set trajectories by controlling position and velocity under ocean current disturbances, demonstrating faster response speeds and more stable behavior compared to traditional PID controllers [9]. A wheeled mobile robot for trajectory tracking experiments is shown in Fig. 2 [10].

Fig. 2 Wheeled Mobile Robot [10]

Obstacle Avoidance: For instance, in intelligent vehicle obstacle avoidance control, the vehicle senses its surrounding environment through sensors to determine obstacle distance, speed, and other information. This information serves as input variables to establish fuzzy rules and fuzzy inference processes, with output variables being the vehicle's steering speed or speed adjustment values. Fuzzy control's adaptability to environmental and parameter changes, combined with PID control, ensures vehicle stability and precision during obstacle avoidance, enabling real-time motion strategy adjustments to avoid collisions.

Path Correction: First, sensors measure parameters such as the deflection angle to the target point and center distance deviation. The fuzzy control algorithm precisely calculates the speed difference between left and right wheels, transmits this information to the controller for processing, and then controls rotation speed to adjust motion status in real-time [11]. In crane deviation control systems, which exhibit time-varying and nonlinear characteristics causing object parameters and structure changes, fuzzy PID control systems can adjust parameters based on real-time crane status to achieve precise deviation control.

Speed Control: In autonomous driving systems, fuzzy PID control can adjust parameters based on real-time detection of errors and error change rates between actual and target vehicle speeds, effectively controlling wheel speed. Thus, mobile robots can quickly reach and maintain target speeds through fuzzy PID control, with significant improvements in control precision. Fuzzy PID has been applied in DC motor speed regulation systems, servo control systems, and vehicle cruise systems. An example of driving robot application is shown in Fig. 3 [12].

Fig. 3 Driving Robot Application [12]

4. Signal Stability Analysis

In fuzzy PID systems, signal stability is a crucial performance indicator and fundamental to ensuring normal system operation. When uncertainties or external disturbances occur, it helps maintain system controllability and reliability while preserving good control effects. Through signal stability, systems can accurately identify input signal changes, understand dynamic characteristics, design better fuzzy rules, and thereby better adjust PID controller parameters to improve system precision and response speed, ultimately enhancing system performance.

4.1. Analysis Methods

Apply Lyapunov stability theory to fuzzy PID controllers, constructing fuzzy Lyapunov functions to analyze nonlinear relationships within the system and system behavior in nonlinear environments, evaluate performance changes, and determine data convergence and system stability [13].

Analyze stability conditions of fuzzy control systems. For example, analyze relationships between inputs and outputs established by fuzzy rules, observe changes, and ensure fuzzy rule rationality to guarantee stable system operation.

PID parameter self-tuning involves real-time parameter adjustment to respond to system changes, evaluating system stability by analyzing the fuzzy logic controller's PID parameter adjustment process.

Simulation and experimental verification simulate system dynamic response and stability performance to further verify experimental results and ensure system stability.

4.2. Influencing Factors

The rationality of fuzzy rule design; study relationships between PID parameters and fuzzy controller outputs, reasonably select optimal PID parameters; external disturbances or internal parameter changes can affect system instability, leading to performance degradation and system malfunction.

Therefore, it is necessary to optimize fuzzy rules, membership functions, and other parameters to improve the fuzzy controller's ability to recognize and process input signals, thereby enhancing adaptability and control precision. Study fuzzy relationships between PID parameters and fuzzy controllers, implement real-time PID parameter self-tuning to improve control precision and enhance system robustness. Additionally, design reasonable hardware systems and develop comprehensive software systems to ensure system stability and reliability.

5. Discussion

Related literature has universally adopted the combination of fuzzy control and PID control, validating through simulation or experimental results that fuzzy PID control can effectively reduce overshoot and oscillation phenomena during motion, although specific implementation methods and application scenarios differ. Some studies emphasize the importance and advantages of fuzzy PID control in improving robustness and stability, while others focus more on fuzzy PID control's contributions to system performance enhancement and feasibility. This demonstrates that fuzzy PID control consistently shows stronger adaptability and stability compared to traditional controllers. In recent years, researchers have improved fuzzy rule design, optimized control algorithms, adopted more advanced parameter tuning methods, and introduced fault-tolerant control strategies to enhance system performance.

Fuzzy PID control shows significant advantages over traditional PID control in mobile robot applications, such as autonomous vehicles and service robots, notably improving precision and stability while enabling real-time parameter adjustment with stronger adaptability. However, it still has some limitations. When mobile robots operate in extreme or unstable environments, such as deep-sea environments or extremely cold regions, where external disturbances are severe, or when systems experience internal failures with nonlinearity and time delays, fuzzy PID control requires extensive calculations and complexity for fuzzy inference and parameter adjustment. This computational burden is particularly challenging in high-frequency real-time control scenarios, affecting control performance and stability with limited robustness and disturbance resistance. Additionally, fuzzy controllers often rely on expert experience, lacking unified standards and automated tools. Environmental variations may lead to inaccurate fuzzy rule design and parameter settings, resulting in steady-state errors that fail to meet ideal requirements.

Therefore, improved particle swarm optimization (PSO) algorithms can be used to optimize PID parameters, finding optimal PID parameters through iterative search. Traditional PID parameter tuning methods often rely on experience and struggle to obtain optimal parameter combinations, while PSO expands the search range and improves accuracy. The improved PSO algorithm enhances global search capability and particle swarm diversity, helping escape local optima. Through adaptive methods, key particle swarm parameters are fine-tuned to better balance global and local search capabilities, distinguishing superior particles from ordinary ones to improve convergence speed and optimization effects. When particles approach optimal solutions, acceleration coefficients can be reduced for precise searching, finding the best PID parameter combinations for current problems. This approach better adapts to complex system changes and improves control system robustness and response speed in unstable environments, reducing steady-state errors and human intervention, thereby further enhancing control system performance.

The improved particle swarm algorithm optimization fuzzy PID control flow chart is shown in Fig. 4.

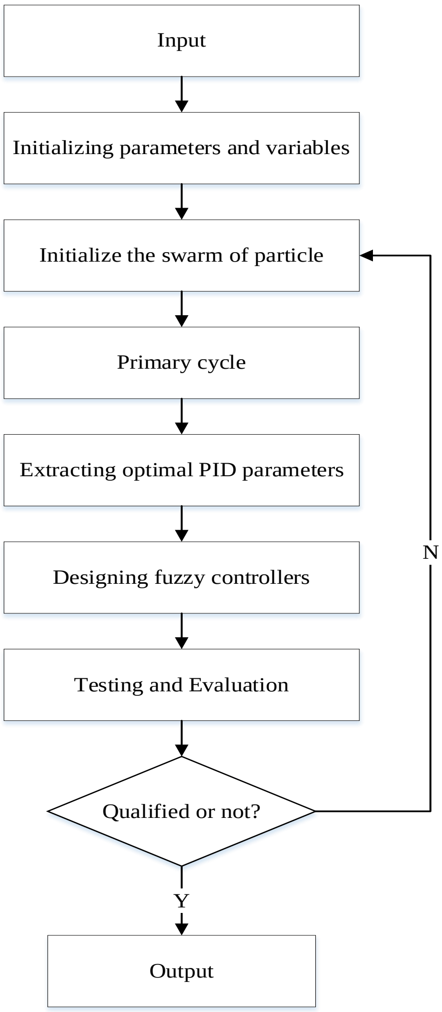

Fig. 4 Improving Particle Swarm Optimization Algorithm to Optimize Fuzzy PID Control Flow Chart

6. Conclusion

This paper reviews research on mobile robot signal stability based on fuzzy PID control, summarizes fuzzy PID principles, and proposes a series of motion control strategies combining fuzzy PID control to address the complexity of mobile robots in practical applications. It illustrates applications in mobile robots such as path tracking, obstacle avoidance, path correction, and speed control, while analyzing signal stability. The research has achieved significant results through continuous breakthroughs in theory, simulation, and practice. In complex, nonlinear systems or environments, fuzzy PID control utilizes fuzzy logic control to compensate for traditional PID controller shortcomings, online adjustment and optimization of PID parameters, improving system stability and performance. As researchers delve deeper into robot control technology, certain aspects still require improvement and optimization, integrating with other advanced technologies such as combining intelligent algorithms to optimize fuzzy algorithms and utilizing multi-sensor fusion technology to enhance robots' environmental perception capabilities for achieving higher-level intelligent control. In the future, through research and continuous optimization across multiple aspects, significant progress is expected in improving system stability and various performance metrics, with fuzzy PID control playing an increasingly important role in mobile robot control.

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