Proceedings of CONF-MSS 2026 Syposium: Mechanical Control and Automation
DOI: 10.54254/2755-2721/2026.BJ32495

Enhancing PID Performance in Mechatronic Systems via Fuzzy Logic and Intelligent Algorithms

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Abstract. The performance of robot control systems directly influences their effectiveness across various industries, agriculture, services, and other sectors. Traditional PID control is widely used due to its simple structure and ease of implementation. However, when facing complex nonlinear systems, time-varying parameters, and external disturbances, its control accuracy and robustness significantly decrease. This paper analyzes the limitations faced by classical PID control in robot applications, with a focus on exploring how fuzzy PID control can adaptively adjust PID parameters by introducing fuzzy inference mechanisms, thereby improving the system's adaptability in uncertain environments. Furthermore, it reviews the integration strategies of various intelligent optimization algorithms, modern control methods, and PID control, including particle swarm optimization (PSO), genetic algorithm (GA), active disturbance rejection control (ADRC), and PID composite control. The results demonstrate the significant effects of these methods in improving robot trajectory tracking accuracy, vibration suppression, and anti-interference ability. It further found that by integrating intelligent algorithms with advanced control strategies, the performance of PID controllers can be systematically improved, providing an effective technical path for the reliable operation of robot control systems in complex dynamic environments.

Keywords: Intelligent Algorithms, Genetic Algorithms, Fuzzy PID Control, PID Control, Mechatronics

1. Introduction

With the rapid development of robot technology, its applications in intelligent manufacturing, precision agriculture, special operations, and daily services are becoming increasingly widespread. Among numerous control methods, proportional integral derivative (PID) control has become the most classic and fundamental control strategy in industrial robots, mobile robots, and servo systems due to its concise structure, clear physical meaning, and easy implementation in engineering. However, robot systems are essentially complex systems with multiple variables, strong coupling, and nonlinearity, and their dynamic characteristics are often influenced by external environmental factors. Traditional PID controllers rely on fixed control parameters, making it difficult to maintain optimal control performance in such complex and changing environments. Therefore, optimizing and enhancing the classical PID control strategy to make it adaptive, robust, and capable of intelligent decision-making has become an important research direction in the field of robot control.

In recent years, intelligent methods represented by fuzzy logic, neural networks, and evolutionary algorithms, as well as modern control theory represented by Active Disturbance Rejection Control (ADRC), have opened new opportunities to enhance the performance of PID control. By combining PID control with these intelligent algorithms or advanced control structures, a hybrid control system can be constructed that combines the simplicity of PID with the adaptability of intelligent methods. This paper explains the limitations of PID control in robot applications, deeply analyzes the optimization mechanism and application value of fuzzy PID control, and further summarize the improvement of PID performance by various intelligent algorithms and modern control methods. By integrating multiple representative research cases in recent times, it also attempts to outline the mainstream technical framework for PID control optimization and intelligent algorithm integration, to provide theoretical reference and practical guidance for the development of higher performance and more intelligent robot control systems.

2. The constraints of traditional PID control in robotic applications

2.1. Basic principles and its robotics applications

To ensure that the robot system achieves precise and stable performance in various environments, PID control is implemented by adjusting the three parameters of proportion (P), integration (I), and differentiation (D) to achieve feedback regulation. This feedback mechanism is a widely employed method in automatic control systems. The output of the controller can be expressed by the following equation [1].

$$u(t)=K_p e(t)+K_i \int_0^t e(\tau)d\tau+K_d \frac{de(t)}{dt} \tag{1}$$

where K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively [1]. The proportional term controls the immediate response to errors, with a larger K_p leading to a quicker reaction. The integral term handles long-term small deviations by continuously accumulating errors, eliminating steady-state errors. The derivative term predicts future error trends, helping to reduce overshoot and improving the overall stability of the system [2].

In robotics, PID control is integral to a variety of applications. For instance, in industrial robots, it is used to convert the desired joint angles into precise motor torques, thereby ensuring the precise positioning of the mechanical arm or legs [3]. Similarly, in mobile robots, PID control plays a key role in maintaining path accuracy by adjusting the wheel speeds, which is essential for autonomous navigation [4,5]. Moreover, in tasks such as force control of robot arms or surgical robots, PID is used to adjust the position or speed of the end effector based on feedback from force sensors, ensuring precise operation and control [6]. And the simplicity and versatility of PID make it the preferred solution in engineering practice, especially in critical industrial settings where precision and real-time response are required to ensure the success of the task [7].

2.2. The limitations of PID control in practical applications

The traditional PID control is widely favored in robot systems for its simple structure and intuitive parameter adjustment. However, when confronted with complex and ever-changing external factors, its limitations become increasingly evident [8]. The nonlinear characteristics of robot dynamics, such as joint friction, elastic deformation in the transmission system, and dynamic effects like Coriolis force and centrifugal force, pose significant challenges [6]. These nonlinear characteristics make it difficult for traditional PID controllers based on linear assumptions to maintain optimal performance under various operating conditions [2,6].

In addition, the uncertainty of robot system parameters presents another challenge. Variations in load, wear of mechanical components, and temperature fluctuations can alter the system's dynamic characteristics, while the fixed parameters of a traditional PID controller make it difficult to adapt to these time-varying changes [3]. Besides, external disturbances, such as vibrations, wind, uneven terrain, or sudden collisions, pose further challenges, severely impacting the accuracy and stability of PID control in real-world scenarios [8,9]. Also, the issue of multivariable coupling is particularly pronounced in robotic systems, where the dynamics of different joints are interrelated [10]. Traditional single-loop PID control often overlooks this coupling effect, leading to degraded overall system performance [5]. For highly coupled Multi-Input, Multi-Output (MIMO) systems, traditional PID control often depends on decoupling strategies or matrix PID structures to handle complex, coupled dynamics, highlighting its structural limitations [11].

2.3. The improvement strategies for PID control

The traditional PID control, due to its fixed parameters and linear structure, has limitations when dealing with dynamic changes and non-linear situations [7]. To address these issues, the recent improvements have focused on parameter adaptive mechanisms, intelligent algorithm integration, and composite control structures [1,3,11]. These strategies have greatly improved the steady-state accuracy, reduced overshoot, enhanced the anti-interference ability, and boosted the robustness and dynamic response capability of the system in complex environments [8,9].

The parameter adaptive mechanism enables the PID controller to dynamically adjust the gains according to the real-time changes of the system [3]. This makes PID control particularly suitable for high-speed and high-load applications, effectively boosting the steady-state accuracy of the system and reducing overshoot [3]. This adaptive adjustment ensures that the system can maintain stable and precise control performance under changing operating conditions [11]. In addition, intelligent algorithm fusion is achieved by integrating PID control with intelligent algorithms like fuzzy logic or neural networks, enabling PID to handle nonlinear systems and unmodeled dynamic behaviors [2,9,10]. And this integration method enhances the response speed of the PID controller and enables it to achieve multi-objective optimization [1]. Especially in complex environments, it can effectively improve the system's anti-interference ability and adaptability, addressing the shortcomings of traditional PID when dealing with high uncertainty [8]. Moreover, the composite control structure combines PID with advanced control strategies like feedforward control or model predictive control (MPC), forming a more powerful control system [5,11]. This composite control architecture boosts system precision and stability, particularly in complex and noisy environments [8]. By combining feedback and feedforward control, the composite control better predicts and resists disturbances, improving dynamic response and tracking [5].

3. The optimization and application of fuzzy PID control in robot control

The combination of fuzzy logic and PID is one of the most typical examples of solving nonlinear and uncertain problems [10]. It uses fuzzy rules to inject expert experience into the controller to achieve parameter self adjustment, hence enabling parameter adjustment for efficient task execution, even in complex external environments [7].

3.1. The principle and mechanism of fuzzy PID control

The basic principle of fuzzy PID control is to combine the fuzzy logic reasoning mechanism with the traditional PID control, thus achieving online adaptive adjustment of controller parameters by simulating the control experience of human experts [7]. This integration relies on establishing a nonlinear mapping between the system state and PID parameter adjustments [2]. To do so, the system error E and the error change rate EC are converted into fuzzy variables through membership functions [10]. Then, reasoning is performed using a pre-designed fuzzy rule base. Finally, the result is defuzzified to determine the precise adjustment values for the PID parameters [2,6].

In terms of implementation, fuzzy PID control can be realized in two primary structural forms. Specifically, one approach involves dynamically adjusting the PID parameters $\mathrm{K_p}, \mathrm{K_i}$, and $\mathrm{K_d}$ in real-time based on the system error E and the error change rate EC, allowing the controller to adapt to changing conditions. The other approach maintains fixed PID parameters and instead directly computes the correction value of the control quantity through fuzzy reasoning, which compensates for the system's nonlinearities and uncertainties. Both of these structures, when applied in real-time tasks, greatly boost the PID control system's ability to handle complex and dynamic environments, offering improved adaptability and robustness [2,7].

3.2. Application and practice of fuzzy PID control

In the practical application of robot control, because the fuzzy PID control is equipped with the control experience of human experts, it has made significant progress in dealing with dynamic problems [10]. In the control of two wheeled self balancing robot, Meng's research shows that fuzzy PID can more effectively deal with the dynamic balance problem of the robot when starting, braking and receiving external thrust [7]. Compared with the traditional PID, its response is more stable, the overshoot is smaller, and the recovery time is shorter. This advantage stems from the fact that the fuzzy controller can intelligently adjust the control strategy according to the real-time changes of inclination error and angular velocity: when the error is large, a strong control force is used to quickly reduce the error, and when it is close to the equilibrium position, the control force is weakened to avoid overshoot and oscillation. In the field of electric climbing robot, Liu's study highlights the superior performance of fuzzy PID control in challenging environments [10]. In the face of the irregularity of the tower structure and wind disturbance, fuzzy PID can control the center of gravity deviation of the robot within 1.5 cm under controlled experimental conditions, such as stable wind speeds and known tower dimensions, by adjusting the attitude control parameters in real time, while ensuring the stability and efficiency of the climbing process. In the application of industrial painting robot, Ji Fuyi's research has proved the effectiveness of fuzzy PID in dealing with nonlinear trajectory tracking tasks. Through fuzzy optimization of the joint control of the six degree of freedom manipulator, high-precision tracking of the painting path of complex surfaces is achieved, and the uniformity of paint film thickness is significantly improved [6].

3.3. Evaluation and improvement of fuzzy PID control

Fuzzy PID control has made obvious improvements in the treatment of dynamic problems, but it still has limitations [10]. Because the fuzzy PID control highly relies on the executive experience of human experts in the process of performing tasks and lacks systematic knowledge reserves, the neutral energy will vary across different problems [2]. Due to the lack of theoretical guidance, the functions and parameters used in the control system are basically selected by trial and error method.

In this process, the errors of functions and parameters will seriously affect the final experimental results. In addition, the calculation process of fuzzy reasoning and defuzzification is relatively complex, which puts forward higher requirements for the computing resources of embedded systems [7]. In view of these shortcomings, researchers have proposed a variety of improvement strategies: one idea is to introduce self-learning and self-organization mechanism, so that the fuzzy system can automatically optimize the rule base and membership function according to the operation data; Another idea is to develop variable universe fuzzy control technology, which can adapt to different working conditions by dynamically adjusting the universe of input and output variables. There is also research on the combination of neural network and fuzzy system, using the learning ability of neural network to optimize the fuzzy reasoning process. These improvements can make the PID control more intelligent and more efficient in dealing with related tasks [11].

4. Enhancement of PID performance through intelligent algorithms and control methods

4.1. Optimization of PID parameter tuning using PSO and GA fusion

To address the issue of traditional PID parameter tuning, which relies on human experience and is inefficient, Zhao et al. proposed an optimization method that combines PSO and GA [1]. This method fully leverages the complementary strengths of the two algorithms. The genetic algorithm offers strong global search capabilities, effectively preventing the system from getting trapped in local optimization, while the particle swarm optimization algorithm guarantees rapid convergence, allowing it to swiftly reach the optimal solution in the later stages of the search. In the specific implementation, the initial population is pre-optimized by PSO, and the individuals with better performance are selected as the initial population of GA, which is then further optimized by GA crossover, mutation, and other operations. The application in the steering control of agricultural robots demonstrates that the PID parameter set obtained through the fusion optimization method can reduce the system's rise time by approximately 30%, lower the overshoot by over 40%, and enhance path tracking accuracy by about 25% in complex terrain conditions. However, the actual performance may vary depending on the experimental platform, parameter settings, and specific environmental factors, and different studies may report slightly different results [8]. This method is well-suited for mobile robot systems with fluctuating conditions and strong controller robustness needs, offering an efficient solution for automatic parameter tuning [1,4].

4.2. Integrated control of adaptive augmented PID and active vibration reduction

By combining adaptive augmented PID control with active vibration reduction, an innovative integrated control approach effectively suppresses residual vibrations in industrial robot joints, even under varying operational conditions. For example, Fan's research proposes an innovative control architecture, which combines adaptive augmented PID with active vibration reduction technology to suppress the residual vibration at the end of the joint of the industrial robot [3]. The system is built around two key modules. The adaptive enhancement control unit analyzes real-time feedback from the joint's dynamic model and adjusts the PID controller's gain parameters online to account for load variations and joint flexibility. Conversely, the active damping unit adopts pulse shaping input technology. It generates shaped control instructions by convolving the reference trajectory with the preset pulse sequence, effectively filtering out the inherent frequency components of the excitation system. The experimental results show that the system can reduce the residual vibration amplitude of the joint end by more than 60% and the vibration energy by more than 70% in the test of the

DR688 dual arm cooperative robot, especially in the complex working conditions of load changes, the system can still maintain stable control performance. The innovation of this integrated control strategy is that it provides a comprehensive solution for the precise control of flexible joint robot from the two dimensions of parameter adaptation and trajectory shaping [3,5].

4.3. Compound control of Active Disturbance Rejection Control (ADRC) and PID

By integrating ADRC and PID control, disturbance rejection and control accuracy can be markedly improved in dynamic and unpredictable environments [8]. For instance, Wang et al. designed a compound control scheme combining ADRC and PID for the inner and outer loops to address the disturbance suppression challenges encountered by underwater vehicles in complex water flow environments. In this scheme, an ADRC is used in the outer loop, where its extended state observer (ESO) estimates and compensates for internal and external disturbances in real time, including model uncertainty and flow impact. The inner loop employs a traditional PID controller, which accurately tracks the speed command output from the ADRC. This clear division of labor allows the ADRC to focus on disturbance suppression, creating a relatively "clean" control environment for the inner loop PID, while the PID leverages its advantage of high tracking accuracy to achieve precise speed regulation [8,11]. The test data on ardusub experimental platform show that compared with the traditional traditional PID control control, the maximum tracking error of adrc-pid under simulated wave interference is reduced by about 0.6 meters, the adjustment time is shortened by 0.8 seconds, and the fluctuation amplitude of control output is reduced by about 40%. This achievement provides an important reference for the control system design of underwater robots and aircraft operating in strong interference environment [8,9].

5. Conclusion

This paper investigates the limitations of traditional PID control in complex robotic applications, especially under nonlinear, time-varying, and uncertain conditions, and looks at enhanced strategies to overcome these challenges. The use of fuzzy PID control demonstrates a notable enhancement in adaptability and robustness by integrating expert knowledge and real-time parameter adjustment, allowing for more efficient management of dynamic balance, trajectory tracking, and environmental disturbances. Furthermore, the integration of intelligent optimization algorithms such as PSO and GA with PID controllers offers an automated and efficient approach to parameter tuning, yielding measurable gains in response speed, overshoot reduction, and tracking accuracy. In addition, the combination of PID with advanced control architectures like adaptive augmented PID with active vibration suppression and ADRC-PID composite control offers complete solutions for vibration reduction, disturbance rejection, and precise control in challenging operational environments. These hybrid control frameworks overcome the limitations of classical PID, enabling more adaptive, robust, and high-performance robotic systems, and providing valuable insights for next-generation intelligent control systems in complex applications.

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