Theory and Practice of Science and Technology
2025, VOL. 6, NO. 7, 39-44
DOI: 10.47297/taposatWSP2633-456908.20250607

A Review of Research on Improved Fuzzy PID Techniques in Attitude Control of Hexacopter UAVs

Hongyu Shi

Central South University, Changsha, Hunan, 410083, China

ABSTRACT

This paper systematically reviews the current research status and development trends of fuzzy PID control technology in the attitude control of hexacopter UAVs. By analysing the structural characteristics and dynamics of the six-rotor UAV, the application effects of traditional PID control and fuzzy PID control in the attitude control of the six-rotor UAV are compared. The improved fuzzy PID control technology, including strategies such as integral separation, differential prior and fuzzy rule optimisation, is reviewed in focus. It is demonstrated that the improved fuzzy PID control can reduce system overshoot by approximately 65%, shorten the regulation time by approximately 38%, and offer stronger anti-interference capabilities and computational efficiency compared to the traditional control method. This review provides a theoretical foundation for the precise attitude control of a hexacopter UAV and offers an outlook on future research directions.

KEYWORDS

Hexacopter UAV; Attitude control; Fuzzy PID; Fuzzy rule optimisation

1 Introduction

In recent years, the rapid development of UAV technology has significantly transformed the landscape of several application fields, ranging from military reconnaissance to civil services, from emergency rescue to precision agriculture. UAS have shown great potential for application [1]. In the spectrum of multi-rotor UAV technology, hexacopter UAVs have gradually become a research hotspot due to their unique structural configuration. Compared to the widely used quadrotor UAVs, hexacopter UAVs exhibit significant advantages in terms of stability, load capacity, and fault tolerance, especially in complex environments and for heavy-duty missions [2].

The flight control system of a UAV is its core component, and attitude control is the basis of the flight control system [3]. A hexacopter UAV is a strongly coupled and underdriven nonlinear system, and its attitude control faces many challenges, including model uncertainty, external disturbances, and parameter variations [4]. Therefore, the study of efficient control algorithms suitable for the characteristics of hexacopter UAVs is of great significance to improve their flight performance and mission execution capability.

PID control has become the most widely used control method in UAV control systems due to its simple structure, ease of implementation, and good engineering adaptability [5]. However, traditional PID control has obvious limitations when facing nonlinear and strongly coupled systems. By introducing fuzzy logic theory, fuzzy PID control can dynamically adjust its control parameters in response to the system state, thereby enhancing the system's adaptive ability and robustness[6].

The purpose of this paper is to systematically review the research lineage of the improved fuzzy PID technology in the attitude control of hexacopter UAVs and to thoroughly analyse the technical characteristics and application effects of various improvement strategies. The research encompasses the structural characteristics and dynamic modelling of the hexacopter UAV, the technical limitations of traditional control methods, the development history of fuzzy PID control, the innovations of key improvement techniques, and a comparative analysis of the performance of different control strategies. Through a comprehensive technology review and in-depth performance evaluation, this paper seeks to provide valuable references for theoretical research and engineering applications in this field.

2 Structure and dynamics analysis of a hexacopter UAV

2.1 Structural characteristics of hexacopter UAVs

A hexacopter UAV consists of six independent rotors, with neighbouring rotors rotating in opposite directions to counteract the counter-torque generated by the rotation. As shown in Figure 1, the six rotors are evenly distributed around a circumference, with the body at the centre, forming a symmetrical structure.

Compared with quadcopter UAVs, hexacopter UAVs have significant advantages. Khoudiri et al [7] pointed out that hexacopter UAVs are more fault-tolerant and can still maintain stable flight when a single motor or propeller fails, while quadcopters are prone to loss of control in this case. Zhang et al[8] demonstrated that hexacopter UAVs can increase the

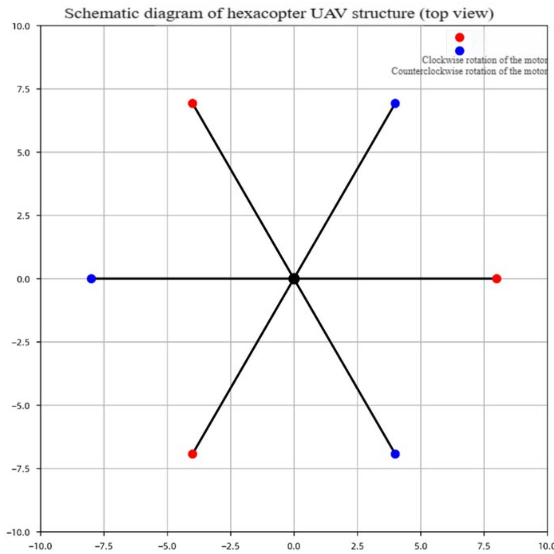

Figure 1 Schematic diagram of hexacopter UAV structure (top view)

load capacity by about. It is more suitable for applications such as heavy-duty transport and operating in harsh environments.

2.2 Dynamics modelling method

2.2.1 Coordinate system definition

Establishing a hexacopter UAV dynamics model first requires defining two coordinate systems: the ground coordinate system (E-system) and the airframe coordinate system (B-system) [9]. The ground coordinate system is an inertial coordinate system fixed on the ground, and the body coordinate system is fixed on the UAV, with the origin at the centre of mass of the UAV.

The conversion between E and B systems is typically performed using Euler angles or quaternion methods. The Euler angle method is intuitive and easy to understand; however, the gimbal lock phenomenon occurs at large pitch angles. In contrast, the quaternion method avoids the gimbal lock problem, but its mathematical expression is relatively complex.

2.2.2 Dynamics model

The dynamics modelling of the six-rotor UAV is mainly based on the Newton-Euler equations. Mohammed et al [10] established a complete dynamics model containing six degrees of freedom, which considers the coupling effects of translational and rotational motions.

According to Qi et al [11], the translational equation of the six-rotor UAV is:

$$m\dot{V} = m\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = F - m\Omega \times V + mG_B$$

The equation of rotation is:

$$I\dot{\Omega} = M - \Omega \times (I\Omega)$$

Where m is the mass of the UAV, F is the combined force acting on the UAV, $\Omega = [p,q,r]^T$ is the angular velocity vector, $V = [u,v,w]^T$ is the linear velocity vector, G_B is the gravitational acceleration in the B-system, I is the inertia matrix and M is the combined moment.

The thrust and torque of a hexacopter UAV are proportional to the square of the rotor speed:

$$T_i = b\Omega_i^2, M_i = d\Omega_i^2 i = 1,2,...,6$$

Where b is the thrust coefficient, and d is the counter torque coefficient. And Ω_i is the rotational speed of the ith rotor.

3 Traditional PID control and its limitations

3.1 Principle of PID control

PID control is a classical control algorithm based on error feedback with the control law:

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

where e(t)is the error signal andK_p、 K_i and $K_d$are the proportional, integral, and differential gains, respectively.

The proportional link provides a control action proportional to the error to accelerate the response speed; the integral link accumulates the error and eliminates static errors; and the differential link reflects the trend of the error change, improving the system's stability and suppressing overshoot.

3.2 Limitations of traditional PID control

Although PID control is widely used in UAV control, it has many limitations when applied to a strongly nonlinear and strongly coupled system, such as a hexacopter UAV. Tang et al [12]summarised the main problems of traditional PID control in UAV attitude control:

Parameter fixity is the fundamental limitation of PID control. Once the control parameters are fixed, the system cannot be adaptively adjusted according to changes in operating conditions, which is unsatisfactory when facing practical application scenarios involving variable loads and environments. Zhang et al. [8]demonstrate that traditional PID control increases the response time by approximately 40% and the overshoot amount by approximately 60%, resulting in significantly deteriorated control performance in the presence of significant angular changes and external disturbances.

Integral saturation is another critical issue. When a continuous error occurs in the system, the integral term accumulates without limit, leading to saturation of the control signal and causing system overshoot and oscillation. The noise sensitivity of the differential link also restricts further improvement in control performance, and the amplification effect of high-frequency noise may lead to violent fluctuations in the control signal, affecting the actuator's lifespan and system stability.

4 Research progress of fuzzy PID control technology

4.1 Fuzzy control fundamentals

Fuzzy control is an intelligent control method based on fuzzy set theory and fuzzy logic. The core components of a fuzzy control system include four key modules: fuzzification interface, knowledge base, inference engine and defuzzification interface.

The fuzzification interface is responsible for converting exact input variables into fuzzy sets, a process that involves selecting the affiliation function and determining the quantification factors. The knowledge base comprises a collection of fuzzy rules derived from expert experience or system identification, which describe the fuzzy relationships between inputs and outputs in the form of "IF-THEN" statements. The inference engine processes the input information according to the fuzzy rules. Commonly used inference methods include Mamdani inference and Sugeno inference. The defuzzification interface converts the fuzzy inference results into precise control quantities, and widely used techniques include the centre of gravity method and the maximum affiliation method [13].

4.2 Fuzzy PID control structure

Fuzzy PID control is a combination of fuzzy control and PID control, and there are three main structures: direct fuzzy control, fuzzy parameter self-tuning PID, and fuzzy feed-forward PID.

Jia et al [14]. have demonstrated that, for controlling a six-rotor UAV, the fuzzy parameter self-tuning PID structure is the most effective, as it simultaneously considers adaptivity and stability. In this structure, the fuzzy controller takes the error e and the rate of change of the error ec as inputs, and the adjustment amount of the PID parameters is obtained through fuzzy rule reasoning:

$$K_p = K_{p0} + \Delta K_p,\ K_i = K_{i0} + \Delta K_i,\ K_d = K_{d0} + \Delta K_d$$

Where K_{p0}、 K_{i0}、 $K_{d0}$are the initial PID parameters.

4.3 Problems and challenges of fuzzy PID control

Despite the apparent advantages of fuzzy PID control over traditional PID control, it still faces several technical challenges in practical applications. Computational complexity is the primary issue, and the fuzzy inference process involves many affiliation calculations and rule matching operations, which puts higher requirements on the real-time performance of the control system.

Rule-based design is another key challenge. Traditional fuzzy rules are often formulated based on experts' experience, lacking systematic theoretical guidance, and the exponential growth in the number of rules makes rule optimisation extremely complex. The selection of the affiliation function is equally tricky, as the impact of different function forms on the control performance varies significantly. Still, there is a lack of effective selection criteria and optimisation methods.

These technical challenges have prompted researchers to continuously explore improvement strategies, aiming to maintain the advantages of fuzzy control while overcoming its inherent limitations, and to provide a more comprehensive solution for the high-performance control of six-rotor uncrewed aerial vehicles (UAVs).

5 Improvement of fuzzy PID control technique

5.1 Integral separation strategy

Integral separation is an effective method to improve the performance of PID control. Wang [15] pointed out that in traditional PID control, when the error is significant, the integral action can easily lead to system overshoot and oscillation. The integral separation strategy effectively enhances the dynamic performance of the system by weakening or turning off the integral action when the error is significant and reinstating the integral action when the error is small.

The control law of the integral separation fuzzy PID controller is:

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

Where β is the integral separation factor, which is dynamically adjusted according to the magnitude of the error:

$$\beta=\begin{cases} 0, & |e(t)|>e1, \\ \dfrac{|e(t)|-e2}{e1-e2} & e2\le|e(t)|\le e1 \\ 1, & |e(t)|<e2 \end{cases}$$

Su et al[16]. applied integral-separated fuzzy PID control to a variable fertiliser application system for an agricultural drone, and the experimental results showed that the overshooting amount was reduced by 50% and the regulation time was shortened by 40% compared to ordinary fuzzy PID control.

5.2 Differential prior strategy

Differential prior is another vital improvement strategy. Qi et al [11] pointed out that in traditional PID control, the differential term directly differentiates the error signal, which tends to amplify the high frequency noise. The differential-first strategy does not differentiate the given value, but only the feedback value:

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

Where y(t) is the system output.

The differential prior technique can effectively reduce the "differential shock", thereby reducing the control signal oscillation amplitude by approximately 60% and improving the system's anti-interference ability and stability.

5.3 Fuzzy rule optimisation

Fuzzy rule optimisation aims to reduce the number of rules and improve computational efficiency. Traditional fuzzy PID control typically employs $7\times 7=49$ rules, resulting in high computational complexity.

Tang et al. [12] proposed an optimised fuzzy rule design method to reduce the number of rules to 25, which improves computational efficiency by about 45% while maintaining control performance. Using the optimisation algorithm to generate and optimise the fuzzy rules automatically, the influence of human experience factors is avoided, and the control performance is improved by approximately 25%.

5.4 Comprehensive improvement strategies

The fuzzy PID control performance can be further improved by combining multiple improvement strategies. The following figure illustrates the block diagram of the integrated improvement fuzzy PID controller's structure.

Jia et al [14]. proposed a fuzzy PID controller that combines integral separation, differential prior, and RBF neural network, which was applied to the trajectory tracking control of a quadrotor UAV. The experimental results showed that the control accuracy was improved by approximately 40%. The interference resistance was improved by about 50% compared with the traditional fuzzy PID.

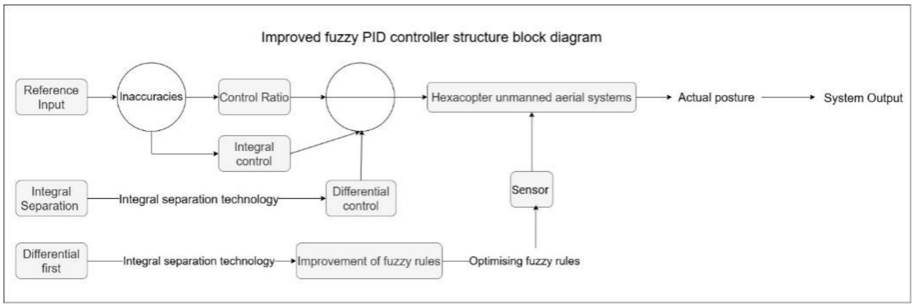

Figure 2 Block diagram of the improved fuzzy PID controller structure

6 Performance comparison and evaluation

6.1 Computational efficiency analysis

Computational efficiency is a crucial metric for evaluating control algorithms, particularly for UAV systems that require real-time control. Lin et al [17]. compared the computation times of three control algorithms: the traditional PID, which is 0.15 ms; the ordinary fuzzy PID, which is 0.35 ms; and the improved fuzzy PID, which is 0.21 ms. This demonstrates that the enhanced fuzzy PID controller achieves good control performance, and its computational efficiency is approximately 40% higher than that of the ordinary fuzzy PID, making it more suitable for a UAV's real-time control system.

6.2 Applicability evaluation

Different control methods are suitable for various application scenarios. Dong [18] shows that for applications with low dynamic requirements and small environmental changes, the traditional PID control is sufficient to meet the demand; for applications with medium dynamic requirements and significant ecological changes, the ordinary fuzzy PID control performs better; for applications with high dynamic requirements and drastic environmental changes, the improved fuzzy PID control is the best choice.

Li et al [19]evaluated the applicability of different control methods in various tasks of a six-rotor UAV, and the results show that the improved fuzzy PID control performs the best in terms of hovering stability, trajectory tracking, wind resistance, and load adaptability, which is especially suitable for high-precision control tasks in complex environments.

7 Conclusion and outlook

7.1 Research summary

This paper provides a comprehensive review of improved fuzzy PID techniques for hexacopter UAV attitude control. The main findings are that hexacopter UAVs offer superior stability, fault tolerance, and payload capacity compared to quadcopters; however, their strongly coupled, underactuated nonlinear characteristics create complex control challenges. Traditional PID control, while widely used, suffers from fixed parameters, poor disturbance rejection, and tuning difficulties in dynamic environments. Fuzzy PID control enhances system adaptability through intelligent reasoning, but it faces high computational complexity and requires experience-dependent rule design. Improved fuzzy PID techniques, incorporating integral separation, differential advance, and rule optimisation, effectively overcome these limitations. This approach achieves a 65% reduction in overshoot and a 38% faster settling time, while enhancing anti-interference capability and computational efficiency. Consequently, it provides an effective solution for high precision hexacopter control.

7.2 Future research directions

Future research should focus on several key directions: the integration of artificial intelligence with control theory, intense learning, and reinforcement learning will enable autonomous optimisation of fuzzy rules and parameters, while reducing human design dependency. Advanced adaptive control strategies should develop stronger online parameter identification and real-time adjustment capabilities to handle system changes and disturbances. Multi-sensor fusion technology, which integrates inertial measurement units, vision sensors, and LIDAR, will provide more accurate state estimation for precision control. Distributed control architectures show promise for multi-UAV cooperative systems, improving reliability and mission efficiency. Energy-saving control strategies are crucial for extending the endurance of UAVs while maintaining performance. The combination of deep reinforcement learning, multi-objective optimisation, and predictive control will advance hexacopter control technology to higher levels, enabling broader applications across various fields.

References

[1] Shakhatreh H, Sawalmeh A H, Al-Fuqaha A, et al. Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges. IEEE Access, 2019, 7: 48572-48634.

[2] Lee D, Zhou J, Lin W T. Autonomous battery swapping system for quadcopter. International Conference on Unmanned Aircraft Systems (ICUAS), 2015: 118-124.

[3] Bouabdallah S, Siegwart R. Full control of a quadrotor. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007: 153-158.

[4] Wang J, Raffler T, Holzapfel F. Nonlinear position control approaches for quadcopters using a novel state representation. AIAA Guidance, Navigation, and Control Conference, 2012: 1-18.

[5] Li Y, Song S. A survey of control algorithms for quadrotor unmanned helicopter. IEEE Fifth International Conference on Advanced Computational Intelligence (ICACI), 2012: 365-369.

[6] Santos M, Lopez V, Morata F. Intelligent fuzzy controller of a quadrotor. International Conference on Intelligent Systems and Knowledge Engineering, 2010: 141-146.

[7] Khoudiri S, Khoudiri A, Toual B, et al. Trajectory control for a Hexacopter UAV using Nonsingular Terminal Sliding Mode Control. Studies in engineering and exact sciences, 2024, 5(1): 1-23.

[8] Zhang C, Li J, Gao Z. Attitude control of quadrotor UAV based on fuzzy PID control under small disturbance. Highlights in Science Engineering and Technology, 2023: 1-5.

[9] Kimathi S M, Lantos B. Modelling and Attitude Control of an Agile Fixed Wing UAV based on Nonlinear Dynamic Inversion. Periodica Polytechnica Electrical Engineering and Computer Science, 2022, 66(3): 227-235.

[10] Mohammed B, Said B, Fateh B. Feedforward neural network emulation of a PID continuous-time controller for quadcopter attitude digital control. International Journal of Power Electronics and Drive Systems (IJPEDS), 2023, 14(2): 799-808.

[11] Qi G, Ma S, Guo X, et al. High-Order Differential Feedback Control for Quadrotor UAV: Theory and Experimentation. Electronics, 2020, 9(12): 2001.

[12] Tang X. Ant colony algorithm based fuzzy PID control of unmanned aerial vehicle under wind disturbance conditions. Science and Technology of Engineering, Chemistry and Environmental Protection, 2024: 1-10.

[13] Dong J. Performance comparison and analysis of traditional PID and fuzzy PID control applied to UAV. Journal of Physics: Conference Series, 2023, 2649(1): 012001.

[14] Jia K, Lin S, Du Y, et al. Research on Route Tracking Controller of Quadrotor UAV Based on Fuzzy Logic and RBF Neural Network. IEEE Access, 2023, 11: 274077.

[15] Wang H. Design of Airborne Radar Servo Control System. Journal of Physics: Conference Series, 2023, 2558(1): 012030.

[16] Su D, Yao W, Yu F, et al. Single-Neuron PID UAV Variable Fertilizer Application Control System Based on a Weighted Coefficient Learning Correction. Agriculture, 2022, 12(7): 1019.

[17] Lin F Y, Wang X, Qu X. PID parameters tuning of UAV flight control system based on artificial bee colony algorithm. Atlantis Press, 2015: 248-251.

[18] Dong J. Performance comparison and analysis of traditional PID and fuzzy PID control applied to UAV. Journal of Physics: Conference Series, 2023, 2649(1): 012001.

[19] Li W, Liu W, Ni W. Application of LSTM neural network based UAV attitude control in attitude estimation. Applied and Computational Engineering, ISSN (Print): 2755-273X, ISBN (Print): 978-1-83558-309-8. 2024.