Application of PID Controllers in Quadrotor UAVs

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Abstract. The proportional-integral-derivative control (PID) is the most popular approach in industry and commerce, due to its simplicity, low cost and effectiveness. Unmanned aerial vehicles (UAVs) have been used widely nowadays, focusing on agriculture, recues and other fields. Quadrotors have nonlinear and strong coupling characteristics, and are underactuated systems due to having fewer rotors than degrees of freedom (DOFs). Therefore, this makes it hard to design a controller. PID has combined with other techniques to create more excellent controllers for its advantages. This paper presents a comprehensive review of PID control applications in quadrotor UAV systems, containing attitude control and trajectory tracking, focusing on the development of linear PID control, nonlinear PID control and adaptive PID control. Linear PID controllers are straightforward in parameters tuning. However, their robustness remains weak, and their adaptability to nonlinear systems is not sufficiently prominent. Nonlinear PID controllers are applicable to nonlinear systems, while plenty of parameter is under tuning. Adaptive PID controller can adjust parameter online according to dynamic scenes, making them suitable for complex environment. At last, 3 kinds of PID controllers are summarized, with the discussion of advantages and shortcomings of each controller, and their future directions.

Keywords: Quadrotor, Linear PID Control, Nonlinear PID Control, Adaptive PID Control

1 Introduction

With the advancement of quadrotor UAVs, many applications have founded for rescue, agriculture, entertainment and so many other fields [1]. Therefore, it's essential to design a more stable controller for quadrotors to adapt to complex environment. Scholars have proposed a variety of control strategies based on different controllers. There are many control strategies designed for quadrotors, such as neural network control, radar cross section (RCS) threat for current combat scenario, and classic sliding mode control [2]. Among these controllers, PID controllers are widely used in various UAVs facilities, owning to their simple design and superior performance.

Essentially, the way of controlling a quadrotor is by regulating the rotational speed of each rotor to modulate the force generated by the rotors, which decide the moving direction of quadrotor. For example, uniformly increasing the rotational speed of all

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rotors simultaneously induces an upward acceleration in the quadrotor. A rotational speed differential between the left and right rotors induces a roll torque, causing the quadrotor to tilt about its axis and fly rightward or leftward, according to which rotor rotating faster. Yaw rotation is generated through differential angular momentum between the four rotors. Thus, the control variables consist of the roll angle, pitch angle, yaw angle, and total thrust [3]. It's noteworthy that the dynamic modeling of quadrotor results in second-order differential equations. The lack of damping terms and underactuated characteristics contribute to the unstable closed-loop system [4].

This paper is trying to survey the evolution of PID control in quadrotors. What should be reminded is that this manuscript only analyzes 3 types of PID controllers, although there are various kinds of PID controllers.

The structure of this paper is organized as follows. Section 2 introduce the quadrotor dynamic model, as well as the control goals. Section 3.1 linear PID control,3.2 nonlinear PID control, 3.3 adaptive PID control. Summary and comparison are given in Section3.4, as well as the future directions of PID control. The conclusion is commented in Section 4 finally.

2 System dynamic model and control goals

The quadrotor UAV which has 6 DOFs (X, Y, Z, roll angle φ, pitch angle θ, yaw angle ψ) is controlled by 4 rotors, being typical underactuated systems. What's more, 4 input signals is required (X, Y, Z, yaw angle ψ) in this system, and there exists mutual coupling between the variables. The quadrotor is affected by wind and other factors when flying. So, to mitigate the impact of disturbances through controller design, the dynamic analysis of quadrotor UAV is particularly crucial.

2.1 System dynamic model and control goals

This section provides a concise description of the quadrotor model. Quadrotor has 6 DOFs, the representation of all the parameters is given in Table 1.

Table 1. parameters and their representation

Parameter	Representation	Related parameter
x	X axis	Velocity $\frac{dx}{dt}$, acceleration $\frac{d^2x}{dt^2}$
y	Y axis	Velocity $\frac{dy}{dt}$, acceleration $\frac{d^2y}{dt^2}$
z	Z axis	Velocity $\frac{dz}{dt}$, acceleration $\frac{d^2z}{dt^2}$
φ	Roll angle	angle velocity $\frac{d\varphi}{dt}$, angle acceleration $\frac{d^2\varphi}{dt^2}$

θ	Pitch angle	angle velocity $\frac{d\theta}{dt}$, angle acceleration $\frac{d^2\theta}{dt^2}$
ψ	Yaw angle	angle velocity $\frac{d\psi}{dt}$, angle acceleration $\frac{d^2\psi}{dt^2}$

Since the lift is actually provided by rotors and is related to their rotational speed, the motor speed (w_1, w_2, w_3, w_4) serve as the input control variables. In this case, the total lift (U_1) and the torques (U_2, U_3, U_4) are given, see (1).

$$\begin{cases} U_1 = b\left(w_1^2 + w_2^2 + w_3^2 + w_4^2\right) \\ U_2 = lb\left(w_4^2 - w_2^2\right) \\ U_3 = lb\left(w_3^2 - w_1^2\right) \\ U_4 = d\left(-w_1^2 + w_2^2 - w_3^2 + w_4^2\right) \end{cases} \quad (1)$$

In this model, under the assumption of a perfectly symmetrical UAV structure, the model can be simplified to (2). I_x, I_y, I_z represent the moment of inertia, m represent the quadrotor mass, and g is gravitational acceleration.

$$\begin{cases} \frac{d^2\varphi}{dt^2} = \frac{U_2}{I_x} \\ \frac{d^2\theta}{dt^2} = \frac{U_3}{I_y} \\ \frac{d^2\psi}{dt^2} = \frac{U_4}{I_z} \\ \frac{d^2x}{dt^2} = \frac{U_1}{m}\left(\sin\varphi\sin\psi + \cos\varphi\sin\theta\cos\psi\right) \\ \frac{d^2y}{dt^2} = \frac{U_1}{m}\left(\cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi\right) \\ \frac{d^2z}{dt^2} = \frac{U_1}{m}\cos\varphi\cos\theta - g \end{cases} \quad (2)$$

2.2 Control goals

The control goals mainly contain hovering, position control and trajectory tracking control. Hovering consists of the attitude control of the quadrotor, setting roll angle and pitch angle to 0, and keeping a constant yaw angle, making the quadrotor fly at a fixed altitude. Position control consists of reaching a specified position and hiking. Trajectory tracking control consist of tracking a specified path in 3-dimensional space.

Quadrotor UAV is mostly controlled by inner-loop and outer-loop, for inner-loop controlling the attitude and outer-loop governing the position, see Fig. 1.

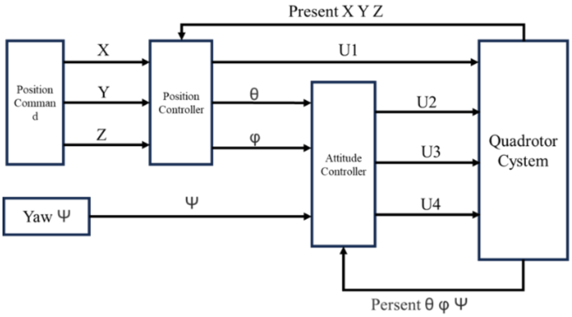

Fig. 1. outer-loop and inner-loop

3 PID-based control of quadrotors

This paper classifies the PID controllers into three types which based on the input-output dynamics of the control system: linear PID controllers, nonlinear PID controllers, and adaptive PID controllers.

3.1 Linear PID control

Controllers based on linear PID control are introduced in this Section. Linear PID controller works on the error signal of target values and actual values, and the system response is proportional to the input, using proportional, integral and derivative to adjust the output. The control law of a linear PID controller is given by (3). $e(t)$ is the error signal. The parameters K_p, K_i, and K_d denote the proportional, integral, and derivative gains, respectively.

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \tag{3}$$

Linear PID control mainly combines with various algorithms or other control strategies to enhance control precision beyond traditional PID method. The gain of linear PID control is fixed, making it easy to design, and the linear PID controller is widely used in industry and other fields [5,6].

In Shahida Khatoon et al., a quadrotor dynamic modeling was given, together with the PID controller design [7]. The efficacy of the proposed control strategy was verified through numerical simulation. While the system achieved zero overshoot and faster transient response, the main problem was excessive oscillation. In Hengameh Noshahri et al. (2014) Feng Lin et al. (2014) and Marc Francis Q. Say et al. (2021), genetic algorithm (GA) was employed to optimized the PID controller gains in order to achieve superior performance than traditional PID controllers [8,9]. It was shown that, in Feng Lin et al. (2014), the system tended to be stable around the time of 100s, much less than the 180s of traditional PID controller, solving the problem between stability and rapidity generally [8]. In Marc Francis Q. Say et al. (2021), this work compared

Tournament selection, Roulette selection, Uniform selection, Stochastic Uniform and Remainder selection [9]. The simulation showed that the PID using Reminder selector had the best step response characteristics, being the best method for the selection. In R.A. Garcia et al. (2012), a robust PID control via affine parametrization was designed and using H∞ theory to ensure the robustness of the system, to make it suitable for the unknown dynamic and disturbance [10]. The simulation showed its excellent performance in nonlinear coupled dynamics. However, an overshoot could be observed with step input. A first-order filter had been designed to mitigate the effect but the time response gets slower, which still was a problem. In Iman Sadeghzadeh et al. (2012), an Active Fault-Tolerant Control (AFTC) technique was integrated into a quadrotor which was controlled by a Gain-Scheduled Proportional-Integral Derivative (GS-PID) controller [11]. Fault-Detection and Diagnosis (FDD) block was based on OptiTrack visual feedback, providing the required inputs for the GS-PID. In fault test, the controller achieved a reduced falling altitude compared to a single PID controller by deciding to switch the controller gains in 0.23s, which demonstrated superior performance in post-failure scenarios. In Christian Neil R. Katigbak et al. (2015), an autonomous trajectory tracking using PID controller was designed for quadrotors. The simulation showed that the steady state error of roll, pitch and yaw angle was small, with a low rise time [12]. The steady state error of altitude was not greater than 5%. It had no oscillations, but the closed-loop system stability had not been verified. In Mohamad S. Chehadeh et al. (2019), a Modified Relay Feedback Test (MRFT) is enough to have near-optimal tuning of the controller within only few seconds [13]. In Lopez-Sanchez Ivan et al. (2020), an experimental parameter identification framework for quadrotors was developed using optimized trajectory [14]. The trajectory was parameterized as a finite Fourier Series. A PID controller was used to implement the tracking of the optimized trajectory, the least-square (LS) algorithm and the gradient descent (GD) algorithm were applied to both standard regression model and filtered regression model, getting 4 labels (LS, GD, FMLS, FMGD). The simulation demonstrate that the proposed method enhanced parameter identifications accuracy, verifying its applicability in complex scenarios.

3.2 Nonlinear PID control

Tables should be formatted as shown in the example below with no column lines, unless these are essential for clarifying the content of the table. Row lines can be used to distinguish the column headings from the content of the table.

In Aws Abdulsalam Najm et al. (2019), a new NLPID controller was presented. The dynamic model of quadrotor also took acceleration and velocity vectors into consideration [15]. 6 NLPID controllers were designed, each having 12 tuning parameters, which were tuned by genetic algorithm. A stability analysis of the closed-loop system was carried out in this paper, proving the stability of the system. What's more, the step reference tracking, trajectory tracking and tracking with disturbances and measurements noise were implemented in MATLAB/Simulink. These simulations fully validated the controller's advantages of fast response, low overshoot, and strong disturbance rejection.

In WeiMin Qi et al. (2006), a NLPID controller based on genetic algorithm was designed, constructing a nonlinear function based on genetic algorithm [16]. This work proved that the NLPID controller could be optimized by genetic algorithm. In Yung-Deug Son et al. (2023), a NLPID controller based on genetic algorithm was designed, having a first-order filter in the derivative term to avoid Derivative Kick [17]. Furthermore, this study specifically targeted First-Order Plus Time Delay (FOPTD) models and employed a singular performance index—the Integral of Absolute Error (IAE)—to derive averaged optimal parameter values. This work also employed the least-squares method to integrate calculated values with the rule formulae, creating new tuning rules. The simulation results encompassed low-order, high-order, and nonlinear processes, demonstrating the method's applicability in complex systems—particularly for high-order and nonlinear systems. Also, the results validated superior specified value tracking and noise robustness, with faster response and lower overshoot in nonlinear systems. In Long Luong Tuan et al. (2013), a sliding mode controller based on PID was designed for micro quadrotors [18]. The *sign* function was replaced by saturation function to reduce the chattering effect in [19]. However, this approach was proved that the system performance would degrade, although the chattering was reduced [20]. Smoothing function was used to reduce chattering phenomenon, resulting in smaller tracking errors, lower energy consumption, and longer operation hours. However, no Lyapunov-based stability proof for the closed-loop system was conducted in this paper, nor was the trajectory tracking performance. In Lamia Melkou et al. (2014), a Terminal Sliding Mode Controller (TSMC) was first designed, using Lyapunov function to verify its sliding surface stability. Subsequently, a cascade PID-TSMC controller was constructed, where TSMC served as the inner loop and PID control acted as the outer loop [21]. The TSMC handled high-dynamic processes, while the PID controller improves steady-state performance. The simulation showed a 60% reduction in pitch angle steady state error, a 5-second response time, a 3% roll angle overshoot as well as a 40% shorter recovery time for roll dynamics. In robustness test, the PID-TSMC controller suppressed pitch angle oscillations to 0.005 rad and reduced tracking error standard deviation by 50%. In conclusion, The PID-TSMC controller not only retained the robustness of TSMC, reduced chattering but also improved tracking accuracy.

In Xuan Zhang et al. (2015), a PID controller based on backstepping control with time-delay (BCTND) estimation was constructed. The PID gains were adaptively adjusted through a feedback regulation function [22]. The Monte Carlo simulations demonstrated a 11-14% improvement in linear and circular target tracking accuracy over conventional PID and no overshoot dynamics for both pitch and yaw angles. These results demonstrated that the proposed controller exhibited superior adaptability, smoother attitude angles, and enhanced guidance precision. In Rios H et al. (2018), a finite-time sliding mode observer (FT-SMO) was employed to predict the quadrotor's position, attitude, and velocity while simultaneously identifying disturbances [23]. Also, a continuous Sliding Mode controller (Continuous-SMC) was designed, based on PID controller and 3 continuous sliding mode strategies known as STSMC, NTSMC and TC, to avoid control signal chattering. Subsequently, theoretical analysis which contained Lyapunov function proved that the closed-loop system exhibits global exponential stability and finite-time convergence, also the robustness to noise. The experiment showed that it was possible to achieve high-precision tracking while facing disturbance. In Babak Salamat et al. (2019), A nonlinear term-based dynamic integral gain adaptation was designed, with a more negative Lyapunov function to ensure closed-loop system stability, while controller gains were optimized via Multi-Objective Particle Swarm Optimization (MOPSO) [24]. In Yakoub Nettari et al. (2022), a Super-Twisting Adaptive Backstepping PID Sliding Mode Control (STABPIDSMC) was suggested, which combined backstepping control, SMC, super-twisting algorithm (STA) and adaptive laws [25]. This approach eliminated steady state error via integral sliding surface, and got a smoother control inputs through STA. A comparison between STABPIDSMC, super-twisting integral sliding mode control (STISMC) and adaptive backstepping PID sliding mode control (ABPIDSMC) was conducted in this paper, which proved the signal smoothness, tracking accuracy, and robustness in nonlinear dynamics, uncertainties and external disturbances. In Aws Abdulsalam Najm et al. (2022), a nonlinear PID controller was constructed, combined with an improved Active Disturbance Rejection Control (IADRC) strategy, in order to suppress exogenous disturbances. However, no simulation result was provided [26].

3.3 Adaptive PID control

This section focuses on controllers based on adaptive schemes, while combined with linear or nonlinear PID control. The core of adaptive PID control is online adjustment of PID gains to enable the control system to adapt to changeable environment. In T. Brehm et al. (1993), a simplified design of a hybrid fuzzy logic PID controller was constructed, switching between fuzzy PI and fuzzy PD, while PD was used for fast response and PI for zero steady state error [27]. When both error and error-derivative entered the "Zero " fuzzy set, PI control took over the system. Compared to pure fuzzy PID control, the proposed control strategy simplified the complex rule, making it easy to design. The simulation showed that after a slight overshoot, the outputs could keep at specified values. What' more, switching logic still need refine to prevent oscillations.

In Yanhong Zhang et al. (2009), the fuzzy PID control had been improved [28]. The proportional, integral and derivative gain could be adjusted online according to the fuzzy inference rules. In Rosales C. et al. (2018), a novel trajectory tracking algorithm was presented, as well as a PID controller based on adaptive neuronal technique [29]. The controller adjusted PID gains online via a neural network, employing a hyperbolic tangent (tanh) function to regulate signal amplitude. Extended Kalman filter was used to filter the signals from sensors. This work verified the stability of the system rigorously in dynamic environment, using the discrete theory of Lyapunov. In trajectory tracking test, when the quadrotor followed a “figure-8” path, the parameter of the system kept changing due to the wind. The result showed that the Euclidean error norm of this strategy was markedly lower than that of conventional PID, meaning superior tracking accuracy and better disturbance rejection performance. In Aurelio G Melo et al. (2022), a fuzzy scheduler was introduced to adjust the gain for both the altitude control and the position control, inputs being error and its time derivative. The altitude controller needed to increase response speed when the error was large and only activated the integral term when the error and its derivative was small [30]. The position controller reduced gain during large altitude errors to keep stable flight. The simulation proved that as the load increased suddenly, a little overshoot could be observed while keeping a stable position up to designed height. Moreover, the controller could still be faster via algorithms optimization. In Tong Liu et al. (2020), an adaptive fuzzy fractional-order PID (AFFOPID) controller was developed by incorporating fractional order differential and integral into both input and output variables [31]. The parameter of AFFOPID were tuned via swarm optimization (PSO) algorithm, taking resistance term into consideration. The simulation illustrated that the proposed controller had better performance in tracking velocity and steady errors than conventional PID and Fractional-Order PID. In Qingcai Zhang (2024), a cascade PID controller was taken as the frame, adding Kalman filter algorithm or complementary filtering algorithm [32]. This paper selected the algorithm which had better performance. The fuzzy scheduler was still controlled by error and its derivative. The result of simulation showed that the controller had good control ability for position and attitude angular rate.

3.4 The advantages and drawbacks of these controllers and their future directions

The PID controller only need to adjust three gains. It's cheap and straightforward in design, being a good choice in steady state or small-disturbance scenarios. However, linear PID controllers cannot control the quadrotor precisely by fixed PID gains, for the strong coupling and underactuated characteristics, and the adaptability of complex scenarios is limited, for example, the UAV controlled by traditional PID almost touched the ground when encountering fault scenarios, and safety cannot be guaranteed [11]. The solution is commonly gain-tuning to adapt to different situations. In addition, UAVs are susceptible to wind disturbances and other effects during flight, so linear PID needs to be combined with other robust control strategies.

The nonlinear PID controller introduces the nonlinear control strategies into the controller, which is more suitable for nonlinear models such as quadrotor systems. Compared to linear PID controllers, nonlinear PID controllers have stronger robustness, and can achieve accurate trajectory tracking under disturbances. However, the nonlinear structure introduces extra computation such as sliding mode function, and the design of the nonlinear function also increases the difficulty of parameter debugging, so the use of genetic algorithms for gain tuning is a good choice. However, genetic algorithms require long computation time, being offline computations, and cannot be adapted to all complex environments, so adaptive PID controllers have been introduced. Adaptive PID optimizes the parameters in real time through adaptive schemes such as fuzzy control, so it can respond to complex scenarios to make decisions. However, due to the large amount of computation, the processing speed is still slow, resulting in the inability to respond quickly to changes in the environment. Not only that, the adaptive PID controller also puts higher requirements on hardware, increasing the cost of the quadrotors. Subsequent research can improve the processing speed by optimizing the algorithm to get better adaptability in complex environments.

Thanks to the low cost of linear PID controllers, common commercial quadrotors are still dominated by linear PID controllers, combined with other robust control strategies. PID controllers will still be the main control strategy of researchers in the future, and with the advancement of algorithms and hardware, the active disturbance rejection control strategy will become a trend. However, the stability verification of the new strategies and experimental demonstration still have many problems to be solved.

4 Conclusion

PID control is straightforward and efficient, and the most common control method for quadrotors is PID control. Not only that, PID control is also used in many types of electromechanical products, proving the excellent commercial properties and control ability. Recent research trends in quadrotor control continue to prioritize PID controller design, including linear PID, nonlinear PID, and their combination with other robust control strategies, or with adaptive control strategies. Adaptive PID controllers can adjust the parameters online according to the dynamic scene, making them suitable for complex environments, which is a hot research topic at present.

Attitude and trajectory tracking control can still be accomplished using the simplest PID controller design, and the integration of robust and nonlinear control strategies can significantly reduce the steady error, improve the response speed, mitigate the overshoot and enhance the robustness to disturbances. The use of genetic algorithms and Multi-Objective Particle Swarm Optimization algorithms can reduce the difficulty of gain tuning and optimize the PID gains, getting a better performance of the controller than that of manual gain-tuning. Combining PID control with adaptive control strategies can improve the robustness of the system, but the processing speed of adaptive schemes is slow and still need to be accelerated. It should be noticed that many control strategies do not carry out Lyapunov analysis.

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