A review of quadrotor control methods

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Abstract. Quadrotor play an increasingly important role in emergency rescue and other comparable missions. However, external disturbances such as wind gusts and turbulence have a great impact on the stability of quadrotor, which means the control system of the vehicle needs to have a strong capability of anti- disturbance. This paper discuss the latest research on quadrotor control methods, and analyzes their characteristics and application. Traditional methods are improved and enhanced in order to attain better control performance. Meanwhile, artificial intelligence and hybrid control methods have garnered extensive research in the realm of quadrotor.

Keywords: Quadrotor ;Linear ;Nonlinear ;Hybrid control ; Intelligent control ;Review.

1. Introduction

In recent years, quadrotor have attracted many researchers' attention, which is mainly due to the performance of flexibility and versatility [1].The number of quadrotor have significantly increased in various field. In the military, quadrotors are used to perform for tactical tasks such as airborne early warning, target reconnaissance , electronic interference. In the civilian, the application of quadrotor include activities such as plant protection, fire prevention, pipeline exploration and 3D mapping [2].

However, the motion of the quadrotor system show strong nonlinearity due to the nonlinear terms in the dynamical systems, such as the cubic term of angular velocity and the quadratic term of torque. The motion of the quadrotor is determined by the thrust generated by the four motors together, and the output force vectors of the four motors are coupled with each other. Therefore, the control of quadrotor require to consider the coupling of multi-variable.

Meanwhile, quadrotor system is a typical under-actuated system, which needs to control the attitude and position simultaneously with only four rotors. It is essential to consider how to use under-actuated characteristics to control attitude and position [3].

Speed and agility are the basic requirements for quadrotor, especially in the missions of emergency rescue and target reconnaissance. But external disturbances such as wind gusts and turbulence have a large impact on the stability, which mean the control system need to have a strong capability of anti-interference. And the effect of dynamic model errors will be amplified during fast maneuvering, which makes it require a strong capability of self-adjustment. In addition, the unpredictable changes of external environment also propose higher demand for robustness [4].

2. Control Classification

At present, the control methods of quadrotor can be divided into linear control, nonlinear control, artificial intelligent control and hybrid control.

The linear control can ensure the stability of the system within a certain range, which is suitable for the control problem of a linear system with a single objective, but cannot deal with the problem that the system model is inaccurate or have uncertainty.

Nonlinear control is used to deal with nonlinear system with multiple cross-coupled and interacting variables, which can effectively resist the effects of external disturbances and uncertainties. The difficulty lies in how to construct accurate mathematical models and design appropriate control strategies.

Artificial intelligent control can be considered to apply the system that is nonlinear and dynamic characteristics are complex, which use artificial intelligence and intelligent algorithms to achieve. This method rely on a large quantity of data for model training and learning, and is restricted to the situations where computational power is limited or real-time performance is required.

Hybrid control is a combination method of many different controls and strategies, which can make up for the deficiencies of various methods for specific problems to achieve better robustness and adaptability. The design and implementation of hybrid control are relatively complex, requiring consideration of the adaptability of different control methods, integration strategies and parameter tuning.

3. Control Method

3.1 Linear Control

3.1.1 PID Controller

PID controller is generally applied in the quadrotor control system. When controlling nonlinear multivariable, the classical PID controller is modified into a new control method to ensure the system's ability to resist external interference.

A PID controller is designed and proposed using Newton's Euler formula to establish the nonlinear dynamics model, the simulation demonstrate that it can achieve trajectory tracking in small perturbations [5].Another similar study can be found in [6].The authors in [7] developed an implicit PID controller with time and state constrains ,the feedback gain can be obtained by using Linear Matrix Inequalities. The main defect of this controller is the effect of model uncertainty on system stability. Moreover, hyperbolic tangent function is applied in PID controller to control tracking desired position and attitude [8].A adaptive PID control for a quadrotor have been proposed and validated in high precision route tracking applications [9]. In the literature [10] , the adaptive PID control based on Lyapunov functions is also presented to stabilize the quadrotor. Simulation of their proposed reveal that a adaptive PID control is superior to PID control.

3.1.2 Linear Quadratic Regulator

LQR is an optimal feedback control method that enhance the system stability by adjusting the gain matrix. the LQR method is also applicable to control when the nonlinear system is linearized [11].

In order to solve the LQR gains problem in the trial and error method , state variable matrix combined weighting matrix have been adopted to adjust the matrix Q and R weighting matrix dynamically [12].Besides, the Bryson method is applied to determine the initial Q and R weighting matrices, further the parameters is optimized based on trial and error methods [13].Furthermore, the best LQR weighting matrix is calculated by the genetic algorithm in [14], which enhances group trajectory tracking ability, the simulation results prove that tracking performance of the group is improved by 36.00%.In [15], the trajectory error is expressed as an element of SE2 (3) in the LQR, the proposed controller outperformed the conventional LQR in simulation. The authors in [16] presented a LQR dependent on the system state, combined fast thrust and slow body speed into a control system to achieves direct attitude control of the quadrotor.

3.1.3 H-infinity

$H\infty$ control have strong robust performance and is appropriate for linear control problems with cross coupled variables, whose parameters are relatively difficult to solve [17].

In [18],the authors introduced $H\infty$ controller based on system identification ,which used the nominal model of the system and the uncertainty weighting function to synthesize a linear $H\infty$ controller. In [19], A hybrid sensitivity $H\infty$ optimal controller is proposed for over actuated tilt rotors, employed weighting functions of different frequencies to achieve the expected performance of disturbance and noise. The authors in [20] investigated a nonlinear $H\infty$ control with cascade structure ,this method is qualified to deal with the influences of perturbations and measurement errors. In the [21], the authors have been presented adaptive neural network based H∞ control to approximate nonlinear systems, and validate the controller is able to eliminate perturbance.

3.2 Nonlinear Control

3.2.1 Model Predictive Control

MPC is an optimal control method that does not depend on accurate model, which allow the output to be controlled according to specific demands and conditions through model predictive control [22].

In terms of improving the accuracy of trajectory tracking, a control method integrating Gaussian process into MPC is established in [23], which used a Gaussian process to compensate for aerodynamic effects, the experiment revealed that quadrotor trajectory tracking errors can be reduced by up to 70% at high speeds. Meanwhile, Torrente et al [24] taked the real input limitations of the quadrotor into account and introduced nonlinear MPC inserted incremental nonlinear dynamic inversion, the experiment show that the position tracking error is reduced by more than 78% compared with NMPC. Furthermore, the authors in [25] designed a deep learning model based MPC control , and adopted neural network to integrates the dynamic constraints into MPC. Compared to MPC method without neural network, the position tracking error is reduced by up to 82%. In [26], a research that a nonlinear model prediction controller cascades to L1 adaptive controller is proposed， which more enhanced the predictive ability of external disturbances than GP-MPC at least 50%.The author introduced nonlinear model predictive controller based on Lyapunov, and introduced constraint to limits the dynamic range of quadrotor to achieve stability of the closed loop system [27].

3.2.2 Backstepping Control

The backstepping method have high flexibility and fault tolerance. The recursive process from low order to high order is relatively complicated [28].

Virtual filtering command is implemented to address computational complexity of backstepping control. Therefore, this approach eliminated differential signals and achieve trajectory tracking in limited time [29].Backstepping have been developed to integrate many other control methods, so that it can deal with the needs of diverse systems. In [30], the authors employed ant colony optimization algorithm to optimize parameters of the backstepping control , the optimal backstepping controller can successfully select the parameters. Extended state observer is introduced to Nonlinear adaptive backstepping for each quadrotor subsystem, the controller have faster response and higher tracking accuracy compared with the existing backstepping [31].Xuan et al designed a full backstepping controller and derived the control laws of five cascaded subsystems based Lyapunov function [32]. Decentralized backstepping control method is presented for decouple and independently control the motion of tilting rotor quadrotor [33].In the literature[34],the authors investigated backstepping control with correction term based on ST algorithm ,which can solve the trajectory tracking problem in finite time and improve the interference of unconventional quadrotor.

3.2.3 Sliding Mode Control

SMC is a variable structure nonlinear control method, aiming at parameter changes and large perturbations control problems, but it is more complicated in the design of the control law and parameter selection [35].

An adaptive backstepping fast terminal sliding mode controller (BSMC) is proposed, which fast terminal sliding mode control is implemented to address the convergence problem limited time [36].The virtual control law and adaptive switching gain is proposed to the SMC to improved the ability of tracking performance under external wind disturbance [37].In [38] , the study presented a fractional-order hybrid terminal sliding mode control applied to inner and outer loop. Contrasted with the integer order controller, this method have the advantages of high control precision and good tracking performance. Difference with the fast terminal sliding mode control, the authors [39]proposed a adaptive law to adjusted and evaluate unknow disturbance, verified that tracking errors can be stabilized to zero simultaneously in a short finite time. Different from nonsingular terminal sliding mode control, this study adopted the continuous convergence law and singularity free nonlinear sliding surface, the method is proved to reduce sliding mode control gain [40].

3.2.4 Feedback linearization

The core of feedback linearization control is to transform nonlinear system into linear system by introducing state variable transformation. The effectiveness of feedback linearization control methods may be limited for systems that are highly nonlinear and have large uncertainties [41].

A parameter estimation adaptive law based on Lyapunov functions is applied to feedback linearization controller in [42],which reduces the impact of wind interference and uncertainty. Compared with the traditional Feedback Linearization controller, the attitude and altitude errors are reduced by 82% and 53%. Feedback linearization is proposed to inner and outer loop control structure in [43]. which is verified to reduce the model dependence of the control structure in simulation. A hybrid control combined static Feedback Linearization with LQR is proposed ,which have zero steady-state position error and lower errors compared the fully linear control [44]. In [45] , a radial basis function neural network is first reported in Feedback Linearization control to compensate the disturbance estimation error. A feedback linearized controller based on a learned acceleration error model and a thrust delay model is presented in [46], which improve the system response and compensate for uncertainty dynamic model and external disturbances.

3.2.5 Adaptive control

Adaptive control can adjust parameters and control strategies according to system dynamics, and is generally used in combination with other control methods.

Lazim et al. introduced an indirect adaptive control and a direct adaptive control, the transient attitude tracking performance of a quadrotor is enhanced by these two adaptive control methods obviously [47]. The study in [48]presented adaptive convergence law based on the robust adaptive sliding mode controller to enhance the robustness of the SMC, which have better performance than the exponential approach law in terms of response time and robustness. An adaptive control is adopted to integral backsliding controller to estimate the inertia parameters of a reconfigurable quadrotor real time [49]. An integral fractional order sliding mode control based on adaptive control is employed ,which make the system reach the equilibrium point in a finite time [50].

3.2.6 Active disturbance rejection control

Active disturbance control improve system stability by tracking reference signals in real time and estimating and compensating disturbance terms, which involves real-time estimation and compensation of disturbances, require high computational and real-time requirements [51].

The authors in [52] introduced an improved active disturbance control(IADRC) attitude, which adopted third order tracking differentiator and novel non-singular fast terminal sliding mode to improve , it have been proven that more resistant to interference than traditional ADRC and PID controller. A linear active disturbance control is presented for attitude controller, Which removed the tracking differentiator and adopted a linear extended state observer (LESO) to enhance regulation ability [53]. Interference suppression control methods introduced to a dual closed-loop ADRC is investigated, the attitude and position of the quadrotor can be accurately controlled [54].Integrated with SMC , the controller combined the advantage of the SMC and ADRC to improve the response speed in [55], in which SMC is applied to the nonlinear state error feedback control law and regarded tracking differentiator as the angular velocity command. The authors introduced an adaptive genetic algorithm-particle swarm optimization to tune the controller parameters, and employed state error nonlinear control law in the ADRC attitude controller [56].

3.3 Artificial Intelligent

3.3.1 Fuzzy Logic

Fuzzy Logic Control is a control method established fuzzy rules and fuzzy inference. Designing and regulating a fuzzy logic controller requires accurate expert knowledge and experience, which may result in degraded control performance if the knowledge is not adequately or accurately acquired[57].

Extracted the maximum information from the uncertain model, a non-single-point fuzzy logic controller is proposed to enhance trajectory tracking accuracy in the unknown environment [58]. A PID controller based on a fuzzy gain scheduling mechanism is introduced ,which exhibited good simulation results but position controller is affected due to large height error [59].An fuzzy control combined a disturbance observer is developed in [60], which utilized a fuzzy logic to approximate the dynamics model , the experiment show that it can control the six degrees of freedom of the quadrotor accurately. The research in [61] introduced the fuzzy logic to sliding mode control to address the model free external interference .

3.3.2 Neural Network

The neural network have strong adaptive learning ability and nonlinear approximation ability, Improper parameter selection and training methods may lead to degradation of control performance [62].

The paper applied neural networks to adjust the sliding mode controller parameters adaptively in [63], making the sliding mode controller less sensitive to parameter changes. The radial basis function neural networks applied to the a non-singular fast terminal sliding mode control is used to estimate uncertain models online [64].A neural network based geometry adaptive controller is presented , which can compensate for the unknown Aerodynamic force and torque disturbances caused by wind [65].

3.3.3 Machine Learning

The authors in [66] investigated a quadrotor position control randomized strategy ,which adopted a proximity policy optimization (PPO) algorithm and policy gradient .

A trajectory tracking controller based on deep learning is proposed for adapting to flight in unknown environment, in addition to, the method can achieve centimeter level position tracking error [67].The iterative learning control is introduced into the backstepping integral sliding mode control (BISMC) to calculate the unknown disturbance, the simulation show that the controller with iterative learning is superior to BISMC [68].Besides, iterative learning is presented to generate expected swarm flight trajectory for formation controller [69]. The research suggested that iterative learning based a gradient combined with PID control improved the reliability of the attitude controller [70].

3.4 Hybrid control

Fuzzy logic-based sliding mode control approach is proposed for quadrotor and optimized the parameters of SMC by genetic algorithm. However, the main drawback of this control is higher capacity computing and time-consuming [71].The author applied SMC to overcome the problem of manual adjustment of the PID controller parameters. Meanwhile, fuzzy logic is also applied to eliminate the chattering phenomena of SMC [72].Combined Backstepping with SMC method is designed for quadrotor position and attitude in a double-loop control structure [73].Another hybrid control study can be found in [74,75].

4. Summary

Significant control methods are being employed in the design of quadrotors for both linear and nonlinear systems, which can effectively resist the effects of external disturbances and uncertainties. Linear control, nonlinear control, intelligent control, and hybrid control have prominent applications in different aspects. The choice of the appropriate control method depends on the system's dynamic characteristics and control requirements. Further research should be conducted on the control methods of quadcopters in terms of practicality and autonomy, which can enhance the robustness of control method and enable to the expand the mission capability of quadrotor.

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