Model Predictive Control (MPC) for Quadcopter UAV Dynamics: A Technical Overview of Obstacle Avoidance

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Abstract

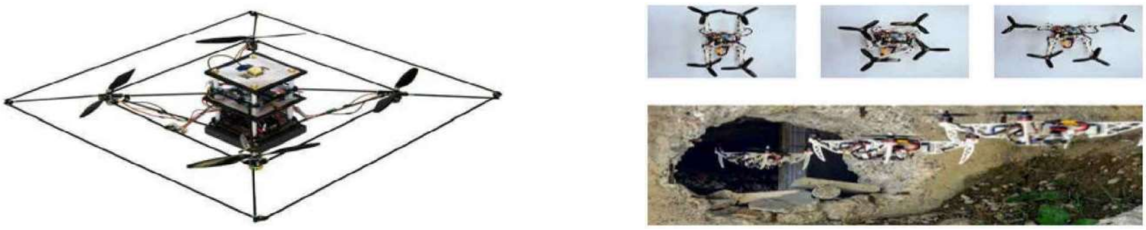
With the continuous progress of UAV technology and the increasingly wide range of application scenarios, quadrotor UAVs have shown great potential in the fields of logistics and distribution, agricultural inspection, and emergency rescue. However, in these application scenarios, UAVs face complex and changing environmental challenges, such as high-rise buildings in cities, irregular terrain in agricultural areas, and uncertainties in disaster sites. These challenges require UAVs to have high-precision path tracking capabilities and dynamic obstacle avoidance to ensure that they can accomplish their tasks safely and efficiently. Meanwhile, Model Predictive Control (MPC), as an advanced control strategy, has received more and more attention due to its ability to deal with constraints and optimize predictions. MPC is well suited to deal with UAV navigation problems in complex dynamic environments by predicting the future state using system models and formulating optimal control decisions based on these predictions. navigation problems in complex dynamic environments. Although MPC theoretically offers the possibility of solving the above problems, research in practical applications, especially in dynamic obstacle avoidance, is still in the developmental stage, and there are many under-explored technical difficulties, such as how to improve the efficiency of the obstacle avoidance algorithm and the robustness of the system under the premise of guaranteeing real-time performance. Therefore, this topic originates from the combination of the practical needs of dynamic path tracking for UAVs and the theoretical development of MPC, aiming to find out the issues that have not been explored or controversial on the basis of combing the existing researches through the technical overview of dynamic obstacle avoidance for MPC quadcopter UAVs, and provide the direction for the subsequent related researches. In addition, through in-depth research in this field, this project also hopes to promote the development of intelligent control systems and provide new ideas and solutions for future automation and intelligent technologies.

Keywords

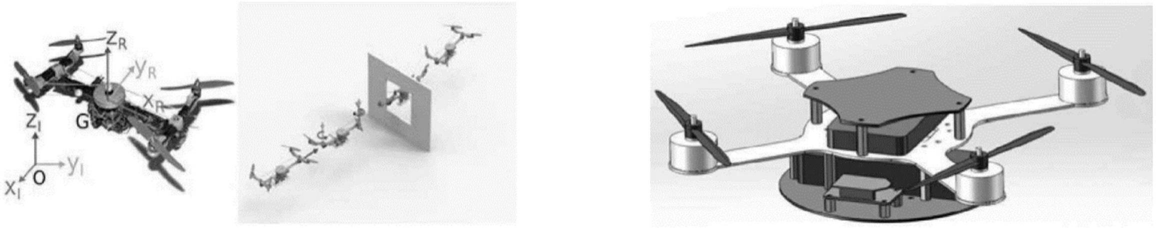
Quadrotor UAV; Model Predictive Control; Dynamic Obstacle Avoidance; Nonlinear Control Method; Machine Learning; Real-Time Performance and Safety.

1. Research Status of Quadrotor UAV

Quadrotor UAV is a typical representative of multi-rotor vehicle, compared with other types of UAVs, quadrotor UAV has a relatively simple structure, strong vertical takeoff and landing capability, excellent hovering performance and other aspects of the technical advantages, has a very broad application prospects. With the rapid growth of UAV application demand in many fields such as logistics and distribution, environmental monitoring, agricultural plant protection, etc., coupled with the adaptability and controllability demonstrated by quadcopter UAVs in low-altitude complex environments, which has achieved a good balance between technological maturity and practicality demand, quadcopter UAVs have gradually become the focus of current domestic and international research. For a long time, key universities at home and abroad have carried out in-depth research around the key technologies of quadrotor design, optimization, and control, and independently developed numerous prototype samples, as shown in Fig. 1 [1].



Stanford University STRMAC UAV University of Zurich Foldable UAV



University of Aix-Marseille Alien Agile UAV Tianjin University Small UAV

Fig. 1 Quadcopter UAVs representing key universities

Advanced control method is the key to realize stable flight, precise control and intelligent obstacle avoidance of quadcopter UAVs, and the research of control algorithm is the core driving force for the development of quadcopter UAV technology. In practical application scenarios, quadrotor UAVs need to deal with other flying vehicles, flying animals and other dynamic targets in real time, and the main focus of current quadrotor UAV research has gradually shifted from basic flight control to dynamic obstacle avoidance technology [2].

2. Commonly Used Linear and Nonlinear Control Methods for Quadrotor UAVs

Quadrotor UAV is a typical multi-input and multi-output nonlinear system, and the control performance of UAV can directly affect the flight stability and mission execution capability of UAV. Aiming at the dynamics characteristics and control requirements of quadrotor, relevant researches have analyzed a variety of types of control strategies, and different methods embody unique application advantages and applicable scenarios, which provide the theoretical basis and technical support for the precise control of rotor UAVs in different application environments.

2.1 PID and LQR Linear Control Methods

Proportional-integral-derivative (PID) control is the most commonly used control method in industrial and commercial electromechanical products, which has outstanding practicality and intuition, and has an important position in the control of quadcopter UAVs.Lopez-Sanchez et al. (2023) pointed out that PID control has been the main choice for controlling the second-order system since its introduction, and that the PID control is able to effectively reduce the steady-state error and effectively compensate for disturbances, errors, and add a damping effect, as well as adding a damping effect to the closed-loop dynamics [3]. In a nonlinear and coupled dynamical system such as a quadcopter UAV, the PID control method has outstanding simplicity and robustness.

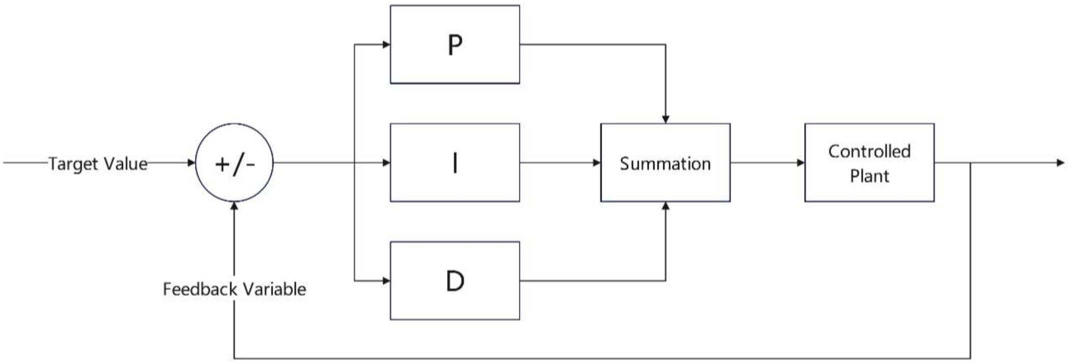


Fig. 2 PID control principle

Linear quadratic regulator (LQR) is also a very important linear control strategy, LQR can be widely used in quadrotor dynamics control based on the optimal control theory of minimizing a given cost function.The LQR controller obtains the optimal feedback gain by minimizing a quadratic cost function that contains the state weight matrix Q, the control weight matrix R [4], and the main advantage of this control method is that it is capable of provide optimal performance while satisfying the system constraints.The key challenge in LQR control optimization focuses on the efficient selection of the weight matrices Q and R. The traditional trial-and-error method of selecting the matrices relies mostly on the practical experience of the designer and does not take into account the effects of uncertainty and disturbances. To overcome this limitation, Elkhatem (2022) studied and proposed an optimization method based on an evolutionary algorithm that is capable of systematically adjusting the weight matrices as well as a robust LQR control strategy based on adaptive weighting matrix selection that can deal with parameter uncertainties and actuator faults more effectively [4].

2.2 Feedback Linearization

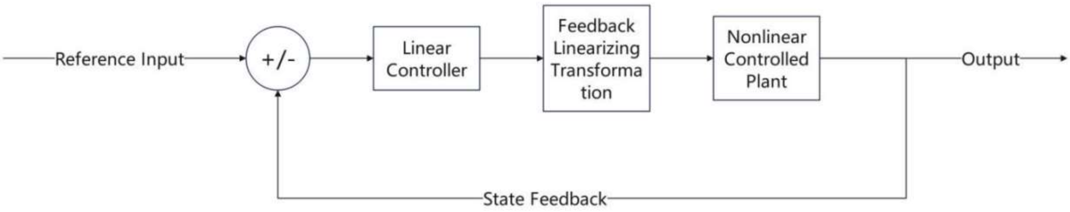


Fig. 3 Schematic diagram of the control principle of feedback linearization

Feedback linearization is a control method that can accurately transform a nonlinear system into a linear system. the core idea of feedback linearization control is to eliminate the nonlinear characteristics of the system through appropriate state feedback and coordinate transformation, and then apply the mature linear control theory for controller design. in the study of Sadiq et al. (2024), it is pointed out that the feedback linearization control method represents the complex nonlinear dynamics model into a standard state space model. model into a standard state-space form, and then through the input-state feedback linearization technique to design an appropriate control law to realize the closed-loop system showing linear characteristics thus greatly simplifying the controller design process [5]. The feedback linearization control method solves the horizontal direction control problem by introducing virtual control inputs, which are cleverly converted into the form of full-drive system. The advantage of the feedback linearization control method is mainly that it can realize the accurate linearization of the system and eliminate the influence of nonlinear coupling terms, and it can directly apply the classical linear control methods such as proportional-differential controllers after linearization, which can significantly reduce the complexity of controller design.

2.3 Backstepping Control

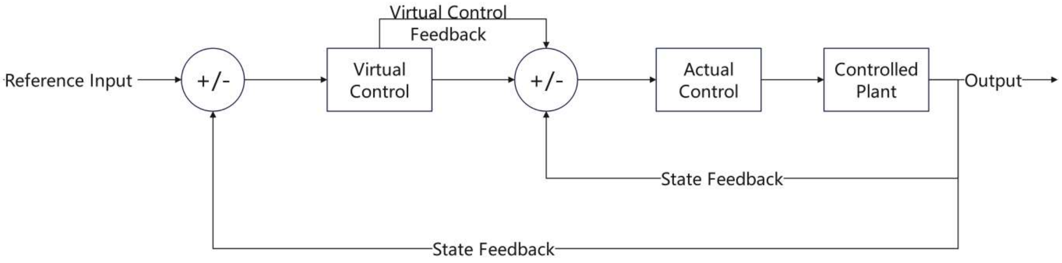


Fig. 4 Schematic diagram of the principle of backstepping control

Backstepping control is a systematic nonlinear control design method, the core idea of this control method is to gradually decompose the high-order nonlinear system into a series of low-order subsystems through a step-by-step recursive design, and gradually construct the virtual control law and the actual control law so as to ultimately realize the stable control of the whole system. Qi Guoyuan (2023) pointed out that the backstepping control method ensures the global exponential asymptotic stability of the closed-loop system through the recursive design of the Lyapunov function, which is very suitable for dealing with the underdriven and strongly coupled nonlinear system in quadrotor UAVs, and it can efficiently deal with the nonlinear characteristics of the system and the dynamic coupling problem, and it can realize the position and attitude of the system through the layer-by-layer design of the control law. precise tracking control [6]. Compared with the traditional PID control and other linear control methods, the backstepping control can show more outstanding adaptability and better control performance in dealing with the nonlinear dynamic characteristics in quadrotor systems.

2.4 Sliding Mode Control

Sliding mode control is a nonlinear robust control method, the basic principle is mainly through the design of the "sliding mode surface", so that the system state slides on the sliding mode surface to achieve effective suppression of system uncertainty and external interference. In quadcopter UAV control, the sliding mode control has outstanding robustness and fast response characteristics, and thus receives a lot of research attention.

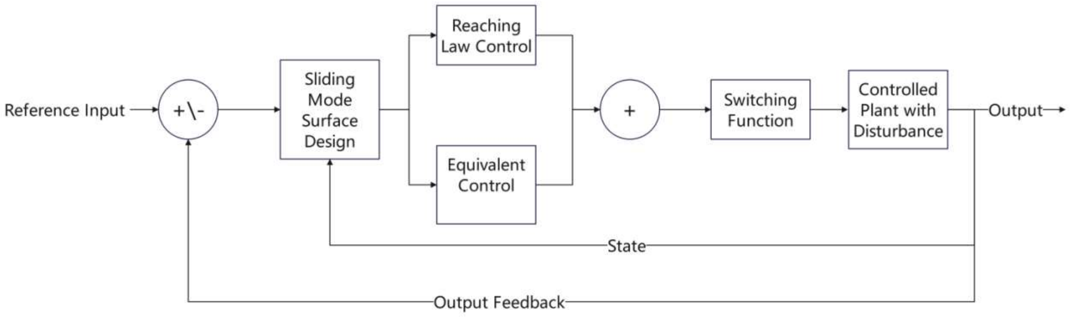


Fig. 5 Schematic diagram of sliding mode control principle

The integrated sliding mode control scheme proposed by Baek et al. (2023), which combines time delay estimation and pole configuration control, can significantly improve the convergence speed and robustness of the attitude-trajectory tracking of quadrotor UAVs, and can effectively deal with the nonlinear characteristics of the system and external disturbances [7]. While the singularity problem is faced in the traditional terminal sliding mode control, when the state quantity tends to 0, the control quantity will tend to infinity. In order to further optimize the sliding mode control, Zhenhua Zhao et al. (2022) studied and proposed a fast non-singular terminal sliding mode control scheme based on an expanding state observer, which treats the coupling between channels and the influence of multi-source disturbances as aggregate disturbances, and estimates and compensates them through the expanding state observer thus achieving finite time convergence of trajectory tracking errors [8]. Liu, Jinhua et al. (2025) further combined the RBF neural network with backstepping sliding mode control and proposed an innovative robust adaptive backstepping sliding mode controller, which is capable of approximating and compensating the nominal control law by the neural network minimum parameter learning method, which can further improve the tracking accuracy and interference resistance [9]. The sliding mode control and its improved methods reflect outstanding application effects in dealing with the nonlinear, strongly coupled and multi-interference characteristics of quadrotor UAVs, which is an effective way to realize high-precision trajectory tracking control.

2.5 Model Predictive Control

Model predictive control belongs to the advanced optimization-based control strategy, and the core principle is to use the explicit dynamic model of the system to predict the influence of future control actions on the system output, and to determine the optimal control sequence by solving the constrained optimization problem, and finally to realize the minimization of the prediction error [10].

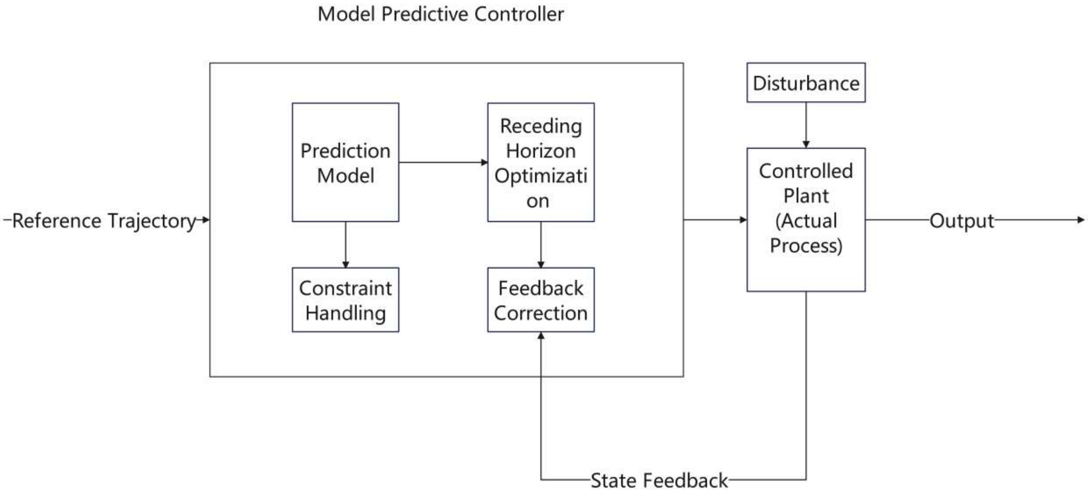


Fig. 6 Schematic diagram of the principle of sliding mode control

Model predictive control performs rolling optimization of the future control trajectory in a certain time domain in each control cycle, thus ensuring that the final computed control inputs achieve the real-time optimum and only the first control quantity of the optimization sequence is executed, and the optimization computation is re-done at the next moment [11]. In quadrotor UAV control, the application of model predictive control also has outstanding application advantages, and this control method can effectively deal with the multiple constraints problem of the quadrotor system, and can accurately analyze the physical limitations in the system, such as actuator saturation limitations, angular and angular velocity constraints, and so on. Meanwhile, the model prediction-based control strategy can further decompose the quadrotor dynamics model into position subsystems and attitude subsystems to realize hierarchical control, which further enhances the modularity and design flexibility of the control system.Yan (2022) also pointed out that optimization improvement of model prediction control by embedding an integrator in the augmented model can eliminate the effects of external perturbations and model uncertainties on the tracking performance without the need for additional disturbance observers [11]. The "predictive" nature of model predictive control makes this control strategy perform well in complex tasks such as quadrotor trajectory tracking and formation control, and it can predict and compensate the system dynamic response in advance, thus significantly improving the control accuracy and robustness.

3. MPC-based Dynamic Obstacle Avoidance for Quadrotor UAVs

In complex dynamic environments, quadrotor UAVs need to deal with system uncertainty and dynamic obstacle avoidance simultaneously, and some studies have explored dynamic obstacle avoidance methods based on constrained optimization.Sun et al. (2024) explored an efficient dynamic obstacle avoidance scheme based on output feedback robust model predictive control in their study. The scheme in the study focuses on quadrotor systems in the presence of unmeasurable states, additive state perturbations, and measurement noise, and mainly employs a Luenberger observer to estimate the unmeasurable states of the system, which decomposes the observer system dynamics into two subsystems, the nominal system and the local uncertainty system [12]. In dynamic obstacle handling, this approach constructs a time-dependent sequence of safety sets based on the time-varying positional trajectories of moving obstacles, after which the concepts of safety sets and pipelines are utilized to cleverly convert a nonconvex dynamic obstacle avoidance constraint into a time-dependent closed polyhedral constraint into a standard deterministic quadratic programming problem that can be solved efficiently.Wakabayashi et al. (2023) studied a dynamic obstacle avoidance approach from another perspective, mainly using an obstacle velocity-based chance constraint approach. This approach achieves avoidance by constraining the probability that the UAV speed enters the velocity obstacle space and thus can effectively deal with high-speed moving obstacles [13]. The advantage lies in the ability to effectively predict the future trajectory of obstacles and start considering the relative velocity relationship in the planning stage, which can realize effective avoidance of high-speed obstacles in environments where a large amount of noise exists. From these studies, MPC mainly relies on mathematical modeling and constraint transformation when dealing with dynamic obstacle avoidance, and this type of method can provide strict security assurance and optimality analysis, which is suitable for scenarios with high security requirements, but the constraint transformation process is more complex, and the assumptions of the obstacle motion model are more stringent.

With the development of machine learning technology, some researches have explored the dynamic obstacle avoidance methods for quadcopter UAVs based on MPC from the direction of machine learning.Du et al. (2024) proposed a quadcopter path planning and dynamic obstacle avoidance method based on the predictive control of nonlinear model in their study. The control method in this study minimizes the control effort and achieves trajectory tracking by optimizing the cost function, converts obstacles into state constraints, and solves the optimization problem by using the Levenberg-Marquardt algorithm, which is able to deal with model uncertainties and perturbations. In dynamic obstacle handling, the method under study models both static and dynamic obstacles as column constraints, and then real-time trajectory planning and obstacle avoidance is achieved through online optimization and then trajectory tracking accuracy reaches 95.2% [14]. Doukhi (2025) proposed a nonlinear MPC method based on simulation-to-display learning, which combines deep learning and nonlinear model predictive control to improve the online optimization process through deep reinforcement learning. This approach excels in challenging tasks such as agile navigation and obstacle avoidance, enables autonomous flight through complex environments and outperforms standard reinforcement learning methods in terms of performance [15]. Learning MPCs represent an important development in dynamic obstacle avoidance techniques compared to traditional methods, which automatically acquire experience from environmental interactions, have greater environmental adaptability and generalization performance, but are also more complex in design, have limited security guarantees and require large amounts of data and computational resources for training.

4. Research Review

Existing research shows that the research of quadcopter UAV control strategy gradually developed from the traditional basic flight control to the diversified intelligent control stage, and the relevant research at this stage mainly focuses on the improvement of methods based on the classical control theory, including the improvement of methods such as PID, LQR, feedback linearization, backstepping control, and sliding mode control, as well as advanced optimization methods based on the predictive control of models, and gradually combines with machine learning to form an intelligent scheme. technology to form intelligent programs. From the perspective of technology maturity traditional control methods are more widely used in engineering practice with higher safety, but advanced control methods are more effective in theoretical research and simulation verification. Different control methods have different advantages and disadvantages in dealing with the dynamic obstacle avoidance problem of quadcopter UAVs, while the traditional linear control method is simple to implement and easy to debug, but has limited effect in dealing with strong nonlinearities and multi-constraints, while the nonlinear control method can better deal with the nonlinear characteristics of the system, but the design complexity is high. Model predictive control shows outstanding potential in both constraint handling and prediction performance, and exhibits significant advantages in dynamic obstacle avoidance scenarios. Existing researches still have certain challenges in solving the dynamic obstacle avoidance problem of MPC-based quadrotor UAVs. There is a contradiction between computational complexity and real-time performance, and the MPC method has a certain computational burden, which makes it difficult to satisfy the real-time control requirements of the fast and dynamic environments, and at the same time, even though MPC can deal with constraints, it still needs to be further improved for safety validation in the learning-based method. Overall, dynamic obstacle avoidance for quadrotor UAVs based on MPC is an important focus of research, and the traditional MPC control method based on constraint optimization is relatively mature, while the intelligent method combined with machine learning shows great potential for application in dynamic obstacle avoidance. Future research needs to focus on the balance of real-time, safety and robustness, and promote the application of intelligent algorithms in it to realize safe and efficient autonomous flight in more complex and dynamic environments.

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