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Research of Different Flight Controls and Methods for Quadrotor Aircraft

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Abstract: The rapid development of unmanned aerial vehicle (UAV) technology, particularly quadrotors, has led to their widespread use in small- to medium-sized applications. This paper provides a comprehensive overview of key flight control strategies for quadrotor UAVs, with a focus on their application in dynamic and complex environments, such as urban areas with tall buildings or forests with dense vegetation. The study discusses traditional methods such as Proportional-Integral-Derivative (PID) control, which is widely used for its simplicity, alongside more advanced techniques like Model Predictive Control (MPC), Adaptive Control, and Active Disturbance Rejection Control (ADRC). Additionally, data-driven approaches such as Deep Reinforcement Learning (DRL) are examined for their ability to adapt to unpredictable conditions, such as sudden changes in wind patterns or unexpected obstacles. Each method is analyzed in terms of its effectiveness in enhancing stability, tracking accuracy, and disturbance rejection, while also highlighting their respective computational requirements and limitations. Future trends, including the integration of hybrid control strategies and advancements in computational power, are explored to improve real-time decision-making and autonomy in UAVs. As the demand for UAVs grows in industries requiring precise and stable flight, further research into these control methods will be critical for advancing quadrotor technology.

Keywords: Quadrotor, ADRC, UAV, PID.

1. Introduction

Quadrotor UAVs are finding increasing applications in various fields, such as agricultural monitoring, environmental surveying, and military reconnaissance. Quadrotor UAVs possess vertical takeoff and landing capabilities, flexible maneuverability, and hovering abilities. These features make them widely used in complex and uncertain environments. However, controlling flight stability and trajectory tracking of quadrotor UAVs remains a significant challenge, especially in the face of strong external disturbances, payload variations, and internal system uncertainties. Effective flight control methods are essential to enhance UAV stability and task execution accuracy, making research on flight control systems highly significant.

Several mainstream flight control methods are commonly applied to quadrotor UAVs, including PID control, backstepping control, MPC, and ADRC. PID control, a classical and widely used method, is valued for its simplicity and ease of implementation. Historically, PID control has been the most commonly adopted approach for industrial systems due to its ability to reduce steady-state error and

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compensate for disturbances, making it a natural choice for UAVs as well [1]. Studies have shown that many flight controllers employ PID control, due to its simplicity and demonstrated effectiveness in stabilizing quadrotors in various real-world scenarios [2][3]. Furthermore, research has shown that PID control schemes can be effectively combined with other methods, such as adaptive or intelligent control, to further enhance their performance [4]. However, PID control can struggle with complex nonlinear systems and may exhibit limitations in environments characterized by strong coupling and dynamic changes [5]. This is because PID controllers are designed based on linear system models and may not adapt well to highly nonlinear or rapidly changing conditions. To provide a comprehensive overview, this paper will explore four main control methods—PID, backstepping, MPC, and ADRC—analyzing their respective advantages and challenges. This paper will provide a detailed comparison to evaluate their performance in different flight scenarios, emphasizing the role of each method in ensuring the stable and accurate operation of quadrotor UAVs in complex environments.

2. Key Flight Control Techniques

2.1. PID Control

PID control has been widely adopted in industrial applications for its ability to stabilize systems by minimizing steady-state error and compensating for disturbances [3]. As such, PID control makes an ideal candidate for controlling quadrotor UAV dynamics, where maintaining stability during basic operations, such as hovering or following set trajectories, is crucial [3]. PID control works well in environments with predictable dynamics; however, it becomes ineffective when dealing with aggressive maneuvers or sudden disturbances like wind gusts. Furthermore, in more complex outdoor environments, PID performance may degrade due to an inability to predict future states [6]. In these instances, PID should be combined with adaptive or robust control techniques to increase its capabilities [7]. As seen in Figure 1, PID control's tracking performance highlights its limitations when handling disturbances [7]. The figure illustrates how its tracking accuracy for both position and attitude tracking suffers under dynamic conditions; further demonstrating its unsuitability for environments with unpredictable disturbances.

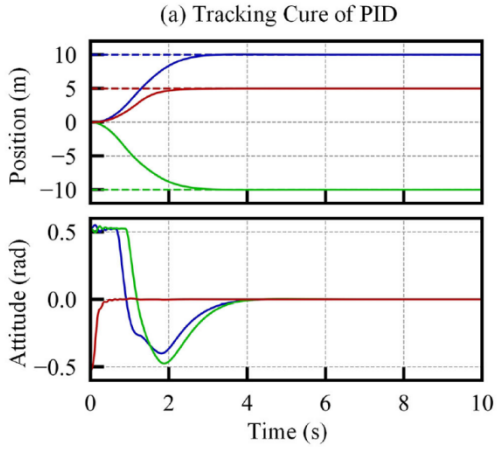

Figure 1: The tacking curves of quadrotor with a controller based on PID [7].

2.2. MPC

In contrast to PID control, which relies on current and historical error data, Model Predictive Control (MPC) utilizes dynamic models of quadrotor systems to forecast future states, enabling more

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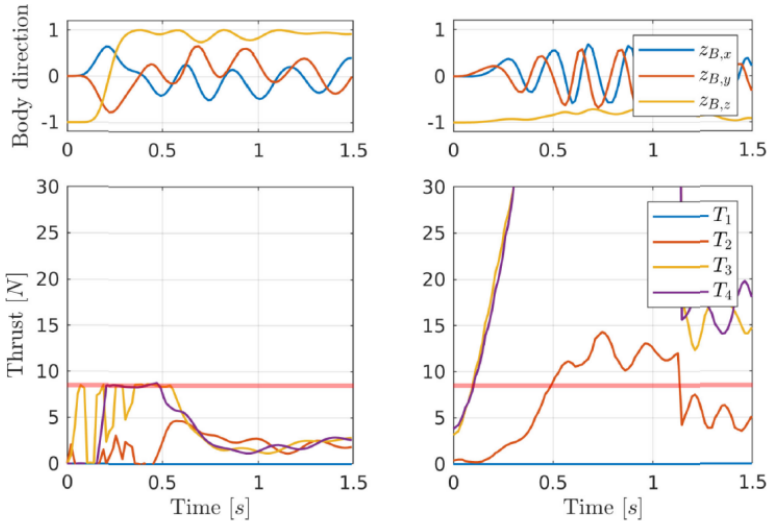
sophisticated control strategies. By optimizing control inputs at each time interval, MPC effectively manages complex systems with multiple variables, ensuring that the UAV adheres to its intended flight path [8][9]. This forward-looking approach renders MPC particularly well-suited for applications requiring continuous real-time adjustments, such as navigating predetermined trajectories and avoiding obstacles [9][10]. Moreover, MPC is highly effective in fault-tolerant control systems, allowing quadrotors to maintain steady flight in the event of actuator failures. This is achieved by reallocating control commands among operational actuators, thereby minimizing interference with UAV operations. Furthermore, MPC considers physical constraints, such as motor power limitations and actuator saturation, thereby enhancing the safety and reliability of the system [11]. However, the primary challenge facing MPC is its high computational demands. Achieving real-time optimization necessitates significant processing capacity, which may restrict its application in smaller UAVs [8][11]. Researchers are actively investigating methods to improve MPC's efficiency without compromising its robust control capabilities. Based on the results shown in Figure 2, NMPC demonstrates superior performance in distributing control commands across the actuators, even during failure scenarios. It underscores how MPC's predictive nature helps quadrotors maintain stability, making it an ideal choice for fault-tolerant applications.



(a) NMPC (b) Benchmark

Figure 2: Quadrotor attitude and thrust commands during a recovery test in simulation. Initial attitude is 180◦ flipped. **(a)** controlled by NMPC, **(b)** controlled by the benchmark controller [11].

2.3. Adaptive Control

Adaptive control is a method that modifies controller settings based on varying circumstances, making it ideal for situations where system parameters or external factors frequently change. This technique is particularly advantageous for quadcopters navigating uncertain environments, such as urban areas or during rescue operations, where factors like wind, temperature, and payload can fluctuate unpredictably [12].

Techniques such as Model Reference Adaptive Control (MRAC) enable the system to adjust control parameters in real-time, ensuring stability. MRAC functions by using a reference model that represents the desired system behavior, and it adapts the control law to minimize the difference between the actual system output and the reference output. This real-time adaptability is crucial for quadrotors operating in unpredictable environments, as it helps maintain the UAV's stability and performance amidst changing conditions. For instance, when a quadrotor faces sudden gusts of wind

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or rapid changes in payload weight, MRAC can instantaneously adjust the control strategy to ensure consistent behavior, a significant improvement over fixed-gain controllers such as PID [13]. Moreover, the ability of adaptive control to dynamically respond to varying flight conditions without extensive manual tuning reduces the complexity of controller design in highly variable environments. This adaptability is essential during rescue missions, where a quadrotor must carry different payloads or operate in areas with turbulent wind patterns. By modifying control parameters to compensate for system variations, adaptive control ensures that the quadrotor can maintain precise maneuverability and stability, despite the presence of disturbances and uncertainties.

Although adaptive control enhances stability in unpredictable conditions, it also introduces challenges. One key issue is the requirement for precise adjustments of the system's adaptive parameters to avoid potential instability. Improper tuning can lead to excessive parameter changes or slow adaptation, which may degrade the performance or even cause instability in the control system [14]. Effective implementation of adaptive control, therefore, necessitates careful calibration to ensure that the system responds appropriately to changes without inducing oscillations or instability. To mitigate such risks, various researchers have developed strategies, such as robust adaptive algorithms that limit the range of parameter adjustments, ensuring stability while retaining the adaptive benefits of the controller.

2.4. ADRC

Having discussed PID and MPC, this paper now turns the attention to another important control method: Active Disturbance Rejection Control (ADRC). ADRC offers an effective and sophisticated method for quadrotor UAVs, mitigating internal and external disturbances by dynamically estimating and compensating for them in real-time. This is achieved using an extended state observer (ESO), which continuously monitors system behavior to estimate the total disturbance acting on it. By doing this, ADRC allows the control system to proactively compensate for these disturbances before they significantly affect performance, ensuring the quadrotor maintains stability during flight [15].

ADRC has proven particularly useful when external disturbances, such as wind gusts, present extreme challenges to flight stability. For this reason, outdoor UAV applications that operate under variable and unpredictable environmental conditions often utilize ADRC; its ability to rapidly detect and adapt to changes in wind speed or direction allows quadrotors with ADRC flight controllers to maintain smooth and controlled flights without experiencing erratic movements or loss of control that would otherwise arise [15].

The extended state observer (ESO) within ADRC is a key component, as it estimates both the internal states and external disturbances affecting the system. Unlike traditional observers, which may require a precise model of the system, the ESO is capable of adjusting to unknown dynamics and uncertainties, making ADRC a more flexible and robust approach for flight control. This adaptability is crucial in real-world scenarios where quadrotors face unknown disturbances and dynamic environments, ensuring reliable control performance. The nonlinearity of quadrotor dynamics is another challenge that ADRC can effectively handle by actively compensating for modeling inaccuracies and unmodeled dynamics. This provides significant advantages over linear control methods, particularly in turbulent and unpredictable environments [6].

ADRC excels in agricultural monitoring applications, where UAVs often encounter unexpected disturbances from environmental forces like wind during tasks such as crop surveillance or pesticide spraying. ADRC's real-time disturbance rejections capabilities help maintain stable flight regardless of sudden fluctuations in wind. Its robustness in dealing with unpredictable external forces increases its adoption in outdoor and remote UAV control strategies [15][16]. Furthermore, compared to Model Predictive Control (MPC), ADRC requires less computational power, making it suitable for quadrotors with limited onboard processing capabilities [16]. This allows ADRC to maintain high

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performance without relying on extensive computational resources, which is particularly beneficial in agricultural and remote inspection tasks where lightweight and efficient control is desired. In addition to its robustness, ADRC's modular structure allows it to be easily combined with other advanced control methods. Researchers have explored hybrid strategies where ADRC is integrated with optimization-based controllers to further improve the stability and efficiency of quadrotors operating under extreme conditions. These hybrid methods leverage ADRC's disturbance rejection strengths while utilizing optimization for trajectory planning and control allocation, leading to more resilient flight behavior in complex and cluttered environments [10].

2.5. Data-Driven Control Approaches

While ADRC provides significant advantages, recent developments have led to new approaches in quadrotor control. Recently, there has been an upsurge in the use of data-driven control techniques, such as machine learning (ML) and deep reinforcement learning (DRL), for managing quadrotors in complex and dynamically changing environments. These methods leverage large datasets to build predictive flight behavior models that adjust to changing conditions without the need for explicit system models [17]. Learning directly from data allows for more flexible and adaptive control strategies, making these data-driven techniques particularly suitable in unpredictable settings where traditional control methods might struggle.

DRL has proven extremely beneficial in helping quadrotors navigate safely through environments filled with obstacles by learning optimal flight paths through trial-and-error processes. Unlike traditional methods that rely on predefined models, DRL-based systems improve their performance by continuously refining control policies to enhance navigation accuracy and obstacle avoidance [17]. DRL stands out among these techniques due to its adaptability in unknown or ever-evolving operating conditions, giving it an edge over traditional methods that rely on predefined models, especially in unpredictable environments [17]. This makes DRL a significant advantage when used alongside traditional methods that rely on predefined models [17].

However, DRL shares certain disadvantages with other advanced control methods, such as model predictive control (MPC) and Active Disturbance Rejection Control (ADRC). Notably, it requires significant computational resources and large volumes of data to train effectively; this requirement could restrict its practical application in real-time control systems, especially for smaller UAVs with limited processing capacities. These computational demands may limit its use in real-time, mission-critical UAV operations.

3. Conclusion

In summary, this paper has investigated various techniques for controlling quadrotor UAVs. These include PID, MPC, adaptive control, ADRC, and data-driven methods such as DRL. Each approach offers unique advantages depending on specific needs and challenges in the operational environment. While PID control is straightforward and commonly used for fundamental stabilization tasks, it may struggle with unforeseen circumstances, such as sudden wind gusts or rapid changes in payload. In contrast, advanced methods like MPC excel in managing complex tasks such as trajectory monitoring and fault resilience, although they are constrained by significant computational requirements.

Adaptive control is characterized by real-time adjustments, making it a valuable asset in environments where conditions are constantly changing. However, it necessitates precise calibration to prevent oscillations. ADRC is particularly effective in mitigating external disturbances, such as turbulence, making it an ideal choice for aerial vehicles operating outdoors. Meanwhile, data-driven approaches like DRL represent a recent breakthrough in UAV control, facilitating self-directed adaptation to novel environments, albeit at the cost of substantial computational resources.

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Looking ahead, the integration of multiple control approaches, such as combining ADRC with DRL, is anticipated to yield more resilient and adaptable aerial vehicles in the future. For instance, this integration could potentially combine ADRC's robustness against disturbances with DRL's ability to learn and adapt to new environments. With advancements in processing capabilities, sophisticated techniques such as MPC and DRL will become increasingly viable for real-time implementation in smaller UAVs, ultimately enhancing performance in complex and dynamic environments. This could lead to applications such as more efficient package delivery in urban areas or more accurate environmental monitoring in challenging terrains.

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