

The Analysis of the Flight Stability Strategy of the Quadrotor

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Abstract. With the rapid development of technology, longitudinal close-range flight recovery / the scenario of application in quadrotor flying, the aerodynamic stability and the position control of the UAV are crucial. This essay systematically examines quadcopters, detailing their classification, aerodynamic principles, control system architecture, and formation flight strategies in complex environments. It highlights the stability and broad applicability of quadcopters among various UAV types, analyzes their propeller configuration and force balance mechanisms, explains control system functionalities, and explores turbulence mitigation techniques for formation operations. The study also summarizes current research achievements and limitations in near-field flight stabilization, providing comprehensive references for future technological advancements to advance controllable and stable close-range UAV flight technology. This research is critical for improving the safety and reliability of UAVs in critical applications such as logistics, surveillance, and disaster response. In addition, this research lays the theoretical and practical groundwork for the future realization of smarter, coordinated and robust aerial systems.

Keywords: Quadcopter, aerodynamic stability, flight principles, control systems, formation flying.

1. Introduction

With continuous advancements in aerospace technology, drones have gained widespread adoption across military operations, agricultural applications, aerial photography, and emergency rescue due to their flexibility, efficiency, and cost-effectiveness. These aerial vehicles primarily rely on wing rotation for aerodynamic flight. The diverse drone categories include multi-rotor drones, fixed-wing drones, and vertical takeoff/landing (VTOL) fixed-wing drones. Among multi-rotor systems, quadrotors have emerged as one of the most widely used drone types today, celebrated for their exceptional stability and versatile applications.

In practical operations, drones typically operate in formation missions where aircraft must enter extremely close proximity and maintain prolonged flight durations. This unique flight state imposes higher demands on drone stability characteristics compared to free-space flight. Unlike free-space flight, close-range operations require not only maintaining aerodynamic stability but also achieving positional stability. Specifically, after external disturbances subside, drones must not only restore their original flight posture but also return to their pre-disturbance relative positions. While most drones achieve aerodynamic stability through aerodynamic design during free-space flights, such designs often fail to meet positional stability requirements. Typically, feedback control using deflection control surfaces is employed to ensure altitude and lateral position stability, while longitudinal (flight direction) position stability primarily relies on engine thrust control. For instance, in aerial refueling scenarios, the receiver aircraft maintains the same speed as the tanker by adjusting its throttle, ensuring longitudinal position stability [1].

This essay mainly studies the response methods of UAVs in complex environments, as well as the flight principles and advantages of the most widely used quadcopter UAV. At the same time, the adaptability of UAVs in complex environments is improved by meeting the requirements of stability criteria [2].

2. The types and application domains of the drones

2.1. The range of application of drones

Drones have now penetrated multiple critical sectors, playing irreplaceable roles across various fields. In military operations, these aerial platforms conduct border patrols by leveraging their extended endurance and agile maneuverability to provide continuous surveillance of borders, enabling timely detection of illegal crossings and other anomalies. Furthermore, they serve as intelligence-gathering assets that support combat decision-making through advanced reconnaissance capabilities.

In agriculture, the application of drones has revolutionized traditional farming practices. Equipped with high-definition cameras and sensors, these aerial platforms can monitor crop growth in real-time, providing farmers with detailed field data on plant development, pest conditions, and disease outbreaks. Furthermore, they enable precision fertilization by delivering fertilizer evenly to target areas based on actual crop needs, significantly improving nutrient efficiency and accelerating agricultural modernization.

In aerial photography, drones have revolutionized filmmaking by providing groundbreaking perspectives. These aerial platforms effortlessly execute complex maneuvers—from low-altitude flights and bird's-eye views to tracking shots—creating visually stunning imagery that elevates content presentation. In emergency response scenarios, they serve as indispensable allies. For power infrastructure maintenance, drones conduct thorough inspections of high-voltage transmission lines and substations, promptly identifying aging cables and equipment malfunctions to ensure stable grid operations. During disaster relief operations, when natural calamities disrupt transportation networks, these agile systems swiftly deliver supplies to affected areas, buying critical time for rescue efforts.

2.2. Main types of drones

Drones are of various types, and different types of drones have significant differences in structural design, flight performance and application scenarios to meet the operational needs of different fields.

Fixed-wing UAV has a similar wing structure to aircraft, fast flight speed, strong endurance, suitable for long-distance, large-scale reconnaissance, mapping, patrol and other tasks.

Multi-rotor drones, with their flexible maneuverability, can perform vertical takeoff and landing, hovering, and low-altitude flight. In addition to quadcopters, there are also hexacopters and octocopters. These drones are widely used in aerial photography, agricultural pest control, close-range reconnaissance, and other scenarios. Among them, quadcopters are the most common due to their comprehensive advantages in stability, cost-effectiveness, and energy efficiency.

Unmanned helicopters have a unique rotor structure and strong flight mobility. They can take off, land and fly in a complex terrain environment. They are suitable for tasks such as material transportation, rescue and air command. For example, in mountain rescue, they can land precisely in a small area to carry out rescue operations.

Vertical take-off and landing UAV combines the advantages of fixed-wing UAV and multi-rotor UAV. It can not only take off and land vertically like a multi-rotor UAV, but also has the characteristics of high-speed flight and long endurance of a fixed-wing UAV. It can perform various tasks in the environment without a runway, such as urban emergency rescue, island patrol, etc.

Paragliding drones utilize wing surfaces as lift generators, featuring simple structures, low costs, and high safety standards. These aircraft excel in low-altitude reconnaissance, aerial advertising, environmental monitoring, and other missions, demonstrating particular advantages in scenarios requiring both cost efficiency and operational safety. In contrast, flapping-wing drones mimic the flight patterns of birds and insects, generating lift and thrust through wing movements. Boasting excellent stealth capabilities and maneuverability, they remain primarily in the research and testing phase. With their technological potential, these drones are poised to play a pivotal role in military reconnaissance and micro-sensing applications.

3. The aerodynamic principle of pneumatic flight

3.1. The basics of four-rotor UAV

Drones primarily rely on wing rotation for flight and stability control, and quadcopters are no exception. In practical operations, these aircraft typically fly in formations. When conducting close-range flights, they must maintain prolonged operation within extremely tight proximity to each other. Therefore, researching the stability characteristics and control technologies of quadcopters in complex flow fields is crucial for ensuring their flight safety.

3.2. Propeller layout and force balance

The propeller configuration and rotational characteristics of quadcopters are crucial for maintaining stable flight. The four rotors are arranged in a clockwise counterclockwise sequence, with identical rotation directions on the same axis. This distinctive design of rotational alignment provides the foundation for counteracting torque forces and sustaining balance during flight.

The four propellers are symmetrically arranged with adjacent blades rotating in opposite directions. During rotation, they generate clockwise or counterclockwise torque forces. The opposing rotational directions of neighboring propellers prevent the drone from spinning due to torque effects, maintaining structural balance and ensuring high safety. Even if one propeller fails, the remaining three can still sustain flight. In such scenarios, the control system rapidly adjusts the rotational speed and output power of the operational propellers. By modifying thrust distribution among the propellers, it compensates for power loss and torque imbalance caused by the faulty propeller, enabling the drone to continue flight or achieve a safe landing while minimizing accident risks.

While hexacopters and octocopters offer greater thrust and potentially higher stability, their larger propeller count leads to increased energy consumption and shorter battery life. In contrast, quadcopters achieve optimal performance through smart propeller configuration and power distribution. This design maintains sufficient thrust capacity and load-bearing capability while significantly reducing battery drain, extending flight duration and making them particularly suitable for extended missions such as prolonged agricultural pest control or border patrol operations.

4. The Control System of the UAV

An accelerometer is an important component in the control system of a quadcopter. During the flight of a quadcopter, the force and moment conditions are complicated, so it is necessary to analyze the flight state and stability through accurate calculation.

The gyroscope plays a crucial role in attitude sensing within quadcopter UAV control systems, precisely measuring the aircraft's tilt during flight. It monitors pitch angle (the vertical tilt of the fuselage) and roll angle (the lateral tilt of the wings). During flight, external factors like airflow disturbances and payload changes can cause fuselage tilting. The gyroscope continuously tracks these deviations and transmits real-time data to the controller. Based on this tilt information, the controller swiftly adjusts propeller rotation speeds to generate counter-torque, effectively counteracting the tilt trend. This ensures the UAV maintains horizontal balance throughout flight, preventing potential crashes caused by excessive tilting.

The magnetic compass serves as a crucial navigation system for quadcopters, determining their heading by detecting surrounding magnetic fields. Equipped with sensors that detect Earth's magnetic field, it measures the drone's azimuth relative to the magnetic north pole, providing directional guidance. Even without GPS or satellite navigation systems—such as in indoor environments, canyons, or high-rise clusters where signals are weak or lost—the compass remains effective. It helps drones maintain approximate flight direction, preventing disorientation and ensuring they stay on course toward mission objectives, thereby guaranteeing successful task execution.

The GPS module performs three core functions: defining flight paths, enabling precise positioning, and tracking the drone's location and speed. Before mission execution, operators can use the ground

control station to plan detailed flight routes for the drone through the GPS module, setting multiple waypoints that the drone will follow sequentially. During flight, the GPS module continuously receives signals from multiple satellites. By calculating the distance between satellites and the drone, it accurately determines the drone's position coordinates on the Earth's surface with positioning precision reaching several meters or higher. Simultaneously, the module measures real-time flight speed to provide controllers with precise motion parameters. Based on these parameters, controllers adjust the drone's flight status to ensure it stays on predetermined routes, enabling tasks like aerial photography, mapping, and inspection.

5. The ways the quadrotor drone deals with the complex environments

5.1. The control system

Cluster controller is an essential core equipment for the formation flight of quadcopters, which plays a role in commanding and coordinating the entire formation control system. The cluster controller is mainly responsible for receiving and sending control instructions, while monitoring the flight status of each UAV in real time.

In terms of command reception and transmission, ground operators send mission instructions to the swarm controller via a ground control station. These include flight path adjustments, operational area changes, and formation transformations. Upon receiving the commands, the swarm controller parses and processes them, then precisely assigns tasks to individual drones based on their current positions and operational statuses. This ensures each drone clearly understands its specific mission requirements and operational parameters [3].

In terms of status monitoring, the cluster controller establishes real-time data connections with each drone to collect flight parameters, including position, speed, altitude, attitude, battery level, and propeller rotation speed. When anomalies occur in a drone's flight parameters—such as deviation from the predetermined route, abnormal speed, or low battery level—the controller immediately triggers alerts and initiates corresponding countermeasures. These may include adjusting the drone's flight status, coordinating with other drones for collaborative operations, or ordering an emergency landing when necessary to ensure the safety of the entire formation.

5.2. The positioning techniques

In order to ensure that the four-rotor UAV formation can fly accurately along the predetermined route and avoid collisions or mission failure caused by position deviation, the formation uses RTK (real-time dynamic positioning) system to preset the flight path of the UAV [4].

The RTK system is a GPS-based high-precision positioning technology. By installing GPS receivers at both a reference station with known coordinates and the drone, the system works as follows: The reference station continuously receives satellite signals, compares its observations with known coordinate data to calculate positioning errors, and then transmits error correction information in real-time via data links to the drone's receiver. The drone processes this corrected data to dynamically adjust its own positioning results, achieving centimeter-level or even millimeter-level accuracy.

Before initiating formation flight operations, operators utilize RTK (Real-Time Kinematic) systems to configure detailed flight paths and waypoints for each drone based on mission requirements and terrain characteristics. During flight, each drone continuously monitors its high-precision position data through the RTK system, which is cross-checked against preset flight paths. The control system automatically adjusts the drone's flight parameters when deviations are detected, ensuring all aircraft maintain strict adherence to predetermined routes while preserving formation stability and coordination within the aerial assembly [5].

5.3. The communications between the UAV

Reliable communication is the key to coordinated flight, information sharing, and unified control of quadcopter formations. Drones need to exchange signals through multiple communication methods while maintaining stable connections with ground control stations, forming a complete communication network.

In drone communication systems, fiber optic pipelines and radio systems are widely used. Fiber optic communication offers high transmission rates, strong anti-interference capabilities, and excellent security, making it ideal for scenarios requiring high data transmission rates and strict communication stability and security standards, such as transmitting HD images or massive sensor data. Radio communication, on the other hand, features high flexibility, extensive coverage, and easy deployment. It effectively handles routine control command transmission and status information sharing between drones, ensuring real-time coordination of flight postures, adjustment of flight positions, and maintaining the overall stability of the formation [6].

Furthermore, drone formations require network connectivity with controllers such as ground control stations. The computer systems at these stations centrally process and analyze flight data from the entire formation. Operators monitor real-time flight status through these systems, sending adjustment commands to the cluster controller based on mission progress and environmental changes to ensure unified command and control. Additionally, the computer systems store and replay flight data, providing critical evidence for post-mission evaluations, fault analysis, and technical improvements.

6. The research results and shortcomings of four-rotor UAV close flight stability control

6.1. The research finding

In terms of the stable control of four-rotor UAV near flight, relevant research has made some achievements, which provide strong support for improving the stability and safety of four-rotor UAV near flight.

Due to the characteristics of disturbed flow fields, drones lack essential aerodynamic/torque feedback mechanisms for directional stability. To address this, researchers propose a method of deflecting elevators by altering drone attitude to redirect aerodynamic forces, thereby simulating the required directional displacement feedback mechanism. This allows drones to recover their original heading position through self-adjustment after external disturbances, enhancing heading stability. Studies also indicate that while thrust control has minimal impact on lateral positioning stability, it significantly improves heading stability. [7] During close-range flight with heading disturbances, adjusting engine thrust enables rapid speed changes to counteract heading displacement, maintaining stability. Furthermore, combining elevator deflection with thrust control yields better feedback performance than using either independently. The coordinated use of both control methods enables comprehensive and rapid response to external disturbances, further improving drone stability during close-range operations like aerial recovery/demanding flights, providing reliable technical support for such applications [8].

6.2. The insufficiency

Although some progress has been made in the research on stable control of four-rotor UAVs in close flight, there are still many shortcomings that need to be further studied and improved.

In the analysis of interference flow fields, current understanding remains insufficient regarding the complex flow patterns generated during close-range flights of quadcopter formations. Research gaps persist in three key areas: formation mechanisms, distribution patterns of flow field parameters, and dynamic characteristics of interference flow fields under different flight conditions. These limitations prevent precise prediction of interference effects on UAV performance, making it challenging to

adequately account for various complex flow interference scenarios when designing control strategies – ultimately compromising control effectiveness [9].

Current active flow control technologies remain underdeveloped. These systems aim to enhance UAV aerodynamic performance and stability by actively modifying airflow patterns through precise intervention. However, existing approaches for close-range flight of quadcopters demonstrate limited effectiveness in controlling near-field turbulence. Both the control efficiency and response speed require significant improvement, as they struggle to dynamically adjust complex turbulent fields in real-time – a critical requirement for maintaining stable drone operations.

In optimal path design, existing methods fail to adequately account for interference flow fields during close-range flight. When planning flight paths for drone formations in close proximity, most approaches only consider factors like mission requirements and terrain obstacles, while neglecting the interaction of interference flow fields between drones. This oversight may result in suboptimal flight paths and in severe cases, could lead to flight instability caused by flow field interference, thereby increasing collision risks.

From a long-term perspective, throughout the century-long history of human aviation, there has been an ongoing pursuit of achieving free aerial deployment and docking of multiple aircraft. However, significant gaps remain in realizing this goal. To accomplish this objective, we need to build upon the existing near-close-range flight stabilization technology for quadcopters by overcoming related technical bottlenecks. This requires developing precise methods to rapidly adjust aircraft aerodynamic forces, conducting more research on interference flow field analysis, active flow control, and optimal path design, while continuously enhancing the controllability and stability of drone operations in close proximity [10].

7. Conclusion

This paper provides a systematic review of research on aerodynamic stability and environmental adaptability in quadcopter flight. As a widely used UAV type with high stability, quadcopters leverage their unique propeller configuration and force-balancing mechanism to effectively counteract torque forces, demonstrate fault tolerance capabilities, and achieve optimal balance between energy consumption and thrust output. Comprehensive control systems incorporating accelerometers, gyroscopes, magnetic compasses, and GPS modules ensure stable flight and precise navigation. For formation flying in complex environments, the integration of cluster controllers, RTK positioning technology, fiber optic pipelines, radio communications, and network infrastructure effectively mitigates interference flow fields between drones, guaranteeing safe and stable formation operations. Additionally, in close-range flight stability research, the proposed deflection elevator flow direction displacement feedback mechanism and the combined use of rudder deflection with thrust control significantly enhance positional stability during short-distance flights.

Future research on quadcopters can be developed from the following perspectives. In the field of disturbance flow analysis, efforts should focus on understanding the formation mechanisms, distribution patterns, and dynamic characteristics of complex disturbance flows. By integrating advanced flow simulation technologies and experimental methods, we can enhance precise prediction capabilities for disturbance flows, providing more reliable foundations for control strategy design. Regarding active flow control technology, developing efficient and rapid intervention methods—such as novel jet control and synthetic jet control techniques—will improve proactive management of disturbance flows, thereby further enhancing UAV aerodynamic performance and stability. For optimal path design, close attention must be paid to disturbance flow impacts during short-range flights. By combining intelligent algorithms, we can create flight paths that avoid flow disturbances while meeting mission requirements, effectively reducing collision risks and improving formation flight efficiency.

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