

Study on the Influencing Factors of UAV Rotor Number on Flight Performance

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Abstract. With the rapid development of developing situations such as disaster monitoring, logistics and distribution, and smart cities, the mission adaptation of unmanned aerial vehicles (UAVs) in complicated environments has become a core issue to be addressed urgently, driving in-depth research on the collaborative optimization of rotor numbers and aerodynamic layout. In dynamic situations, the current rotor configuration models are not very good in terms of prediction accuracy; however, when the number of new energy power systems is integrated with the rotor configurations, there is a weight-efficiency conflict, which prevents the UAV's endurance and mission payload from being further improved. This paper systematically reviews domestic and international research results on the relationship between UAV rotor number and flight performance. By analyzing experimental data and engineering cases, it summarizes the performance of different rotor configurations in terms of flight efficiency, stability, and load capacity. The review shows that the four-rotor structure has good comprehensive performance in conventional applications, while configurations with six or more rotors exhibit unique advantages under special working conditions. In addition to discussing the problems that are still unresolved and the direction of future development in this area, the paper also addresses the requirement of using the multi-rotor system algorithm model and looking into the potential future scenarios of multi-rotor UAVs.

Keywords: Rotor Number Optimization of Multi-Rotor UAVs, Rotor Dynamics Theory, Synergistic Effect of Aerodynamic Interference.

1. Introduction

As an emerging technology, UAVs are likely to gain extensive practical application value in the near future, especially in the fields of traditional surveying and mapping and land cover change monitoring in remote areas. The most challenging problem in UAV applications is to improve load-carrying capacity, which requires selecting appropriate multi-rotor UAVs and conducting systematic design optimization. Cutting-edge technologies such as UAVs have great potential in solving social problems, but their full potential has not yet been fully tapped. Among multi-rotor UAVs, four-rotor, six-rotor, and eight-rotor UAVs have greater advantages in carrying large effective payloads.

Research on UAV rotor number began in the early 21st century and has gradually deepened with the popularization and application of multi-rotor aircraft. According to engineering practice statistics, the number of relevant technical literatures has shown a continuous growth trend from 2015 to 2023, and the research focus has shifted from basic performance testing in the early stage to systematic optimization design at present.

Early traditional analysis methods, mainly based on rotor dynamics theory (momentum theory and blade element theory), established a mathematical model between power consumption and lift. For example, the simulation of a single rotor can be accurately calculated using specific formulas; however, when multiple rotors work together, the airflow interference between them leads to differences between actual performance and theoretical predictions.

In practical applications, researchers such as Zhang Hongle, Qian Jianping, Guo Chun, and Su Wenjie have found that multi-rotor systems have obvious inflow and downwash interference. When the downstream rotor is in the downwash flow of the upstream rotor, its working efficiency decreases significantly. With the increase in the number of rotors, in four-rotor and eight-rotor UAVs, downwash interference exists not only between adjacent rotors but also between diagonal rotors, making the multi-rotor flow field more complex and posing greater challenges to performance

prediction. At the same time, in the face of more airflow interference, the thrust of a single rotor in four-rotor and eight-rotor UAVs decreases more significantly. For example, when the same rotor spacing (axial spacing between the hubs of two rotors) is $2.1R$ (rotor radius), the lift generated by the two-rotor system decreases by approximately 9.2% compared with the non-interference superposition result of a single rotor; further, the lift of the four-rotor system decreases by approximately 10% compared with the non-interference superposition result of a single rotor, which is greater than the lift loss percentage of the two-rotor system (9.2%) [1].

The core objectives of this paper are to provide a scientific basis for the design and selection of UAV rotor numbers through multi-dimensional analysis, and promote the development of multi-rotor technology towards higher efficiency, safety, and scenario adaptability. Specifically, the objectives include clarifying performance boundaries: Systematically summarizing the performance advantages and limitations of different rotor configurations, and establishing a corresponding relationship between "rotor number and application scenario" to provide data support for the selection of models in consumer-grade, industrial-grade, and special mission scenarios (e.g., four-rotor UAVs are suitable for conventional aerial photography, six-rotor UAVs for safety-critical missions, and eight-rotor UAVs for heavy-load transportation). Identifying technical bottlenecks: Focusing on unresolved problems in current research (such as dynamic interference prediction, super multi-rotor control, and new energy integration) to provide direction for subsequent research and promote the integration of theory and engineering practice. Looking forward to future development: Combining technologies such as bionics, artificial intelligence, and new energy to explore innovative paths for multi-rotor systems (e.g., variable rotor design, swarm cooperative control), laying a foundation for improving the adaptability and mission capability of UAVs in complex environments (such as cities and plateaus).

2. Performance Characteristics and Practical Applications

2.1. Performance of Different Configurations

Comparative tests show that the four-rotor structure has good energy efficiency under conventional flight conditions, while the six-rotor system exhibits stronger stability in the event of sudden failures. Configurations with eight or more rotors, although having higher energy consumption, have irreplaceable advantages in special scenarios such as heavy-load transportation.

The benefits of four-rotor UAVs in traditional uses, such as aerial photography and inspection, are obvious. In consumer-grade UAVs, the endurance time of mainstream four-rotor models in typical missions is up to 50% longer than that of equivalent six-rotor models. This is mainly due to the weight advantage brought by the simpler structure and the more optimized aerodynamic layout. However, the four-rotor system has inherent defects in safety: if any rotor fails, it is difficult for the system to maintain stable flight, which limits its application in some critical missions.

With redundant designs, the six-rotor system greatly increases dependability. The unique symmetrical double triangular layout of the six-rotor system enables it to achieve emergency hovering through the remaining five power units even if one motor fails. This feature has made it widely used in fields with high safety requirements, such as power inspection and border patrol. However, the additional rotors also lead to greater weight and higher energy consumption. When compared to the four-rotor version, the empty weight of the consumer-grade six-rotor model of the same model is typically 25%–30% higher, and it also shortens the endurance period by 15%–20%. Configurations with eight or more rotors are mainly designed for special needs such as heavy-load transportation. Test data from Freefly Corporation (USA) shows that the maximum payload capacity of its eight-rotor product, Alta 8, reaches 9 kg. This strong load capacity makes it perform well in film shooting scenarios. Nonetheless, the issue of energy consumption in these models is quite significant; they typically have an endurance time of only 15 to 30 minutes under full load, which somewhat restricts their scope of application [2].

2.2. Practical Engineering Application Cases

In practical engineering, UAVs with different rotor numbers have been applied in various fields. For example, four-rotor UAVs are frequently used in aerial photography and inspection, six-rotor systems in professional surveying and mapping, and eight-rotor models in heavy-load jobs such as material transportation. Some innovative designs have also attempted to adopt variable rotor number schemes to adapt to different flight requirements.

In the consumer market, quadcopter hold a commanding position. Taking DJI's product line as an example, the global market size of four-rotor UAVs is expected to exceed 120 billion Chinese yuan (CNY) in 2025; Chinese manufacturers account for more than 75% of the global market share, among which DJI continues to lead the consumer market with a 58% market share. Such products usually weigh less than 2 kg and have an endurance time of 20-30 minutes, fully meeting the aerial photography needs of ordinary users. In terms of price, four-rotor models also have distinct advantages, with entry-level products priced at less than 500 US dollars [3].

In industrial applications, six-rotor designs are more commonly used, specifically for scenarios such as forest fire monitoring, agricultural monitoring, railway monitoring, and oil and gas exploitation. Such models are more than 60% of the market in the North American market, and the two biggest advantages are: firstly, they are able to return safely even in the event that one rotor malfunctions; secondly, they have greater stability in a variety of weather conditions; and third, they can transport more expensive professional equipment. The price of such products is usually between 20,000 and 50,000 US dollars, mainly targeting professional users.

Configurations containing eight or more rotors display special value in particular application areas. The LTY-460 eight-rotor heavy-lift UAV developed by Liante (Fujian) Intelligent Equipment Co., Ltd. is made of carbon fiber and aluminum alloy composite materials, with a modular structure design and a wingspan of 3.67 meters. Its maximum take-off weight is 230 kg in low-altitude areas and 108 kg in high-altitude areas (at 4,000 meters). The maximum hovering time of the empty aircraft reaches 55 minutes. In the field of heavy-load transportation, it has advantages such as convenient operation, visualized flight process, safety and reliability, flexibility, and no terrain restrictions. Its operating environment covers mountainous and hilly areas, which greatly improves construction efficiency and reduces safety risks [4].

In recent years, systematic simulation designs for the feasibility of UAVs with variable rotor numbers have represented a new technical direction. For example, the Backstepping-PID hybrid control algorithm can be used to adjust motor power, enabling software-simulated switching of the eight-rotor UAV between four-rotor and eight-rotor modes: 4 motors are activated for equivalent four-rotor mode during light-load cruising (reducing power consumption by 20%), and all motors are activated for eight-rotor mode during take-off/landing or anti-interference. MATLAB/Simulink simulations show that the steady-state error under gusts is reduced by 67% compared with the traditional PID algorithm. In the same period, Shen Xueqiang, Fan Jiwei, Xue Tingting, et al. further verified that its thrust vector distribution model can maintain lift stability in four-rotor mode through power compensation. The attitude angle fluctuation under a wind speed of 8 m/s is reduced by 40% compared with pure PID control. However, limited by hardware, the load capacity in four-rotor mode is reduced by 30%, and there is a 0.8-second delay in switching. Such simulation studies provide algorithm support for dynamic rotor adaptation and are suitable for scenarios that require balancing energy efficiency and stability, such as agricultural spraying and power inspection [5].

3. Existing Problems and Development Trends

3.1. Technical Challenges

Current research still faces several key technical challenges: how to accurately predict the aerodynamic characteristics of dynamically changing rotor layouts, how to handle the cooperative

control of super multi-rotor systems (with more than 10 rotors), and how to effectively integrate new energy systems with rotor configurations.

The aerodynamic prediction of dynamic rotor layouts is a complex problem. Conventional CFD (Computational Fluid Dynamics) techniques impose a significant computational burden when addressing flow field changes during rotor retraction and deployment, hindering the ability to meet the real-time demands of engineering design. The latest report from Boeing's R&D department (USA) points out that the error of the simplified model developed by them in predicting lift changes during rotor deployment still reaches $\pm 12\%$, which is far higher than the prediction accuracy requirements for conventional layouts.

The control algorithm for super multi-rotor systems (with more than 10 rotors) also faces challenges. A team from the University of California, Berkeley (USA) conducted experiments on a 16-rotor UAV and confirmed that when the number of rotors exceeds 10, the traditional PID controller has difficulty handling the nonlinear aerodynamic coupling between rotors (downwash interference, thrust distribution delay). Under a gust condition of 5 m/s, the attitude oscillation amplitude reaches $\pm 8^\circ$, which is much higher than that of four / eight-rotor systems (within $\pm 2^\circ$). The research clearly proposes that "it is necessary to break through the traditional single-loop PID architecture" [6].

The integrated application of new energy systems also brings new technical problems. Hydrogen fuel cell UAVs usually require larger installation space and stricter weight control, which conflicts with the structural complexity caused by the increase in the number of rotors. The test data for the Commercial Aircraft Corporation of China, Ltd. (COMAC) in 2023 shows that the weight of the power system accounts for 45% of the total weight of the six-rotor hydrogen-powered UAV, seriously affecting the effective payload capacity. How to optimize the rotor layout to adapt to the characteristics of new energy systems is an important direction for future research [7].

3.2. Future Directions

According to the findings of previous studies as well as the engineering requirements, the following areas might be the main focus of future study: developing more precise rotor interference prediction methods; second, investigating the use of bionics in multi-rotor design; and third, researching safe flight solutions that are modified to fit in urban settings.

In the field of interference prediction methods, hybrid modeling technology integrating machine learning has shown clear application prospects. The combination of technologies such as Factorized Fourier Neural Operator (F-FNO), LSTM (Long Short-Term Memory) deep neural network, and physical constraints has become a key direction to break through the bottleneck of traditional simulation. Airbus Group (Europe) has accumulated extensive experience in this field: it has long achieved accurate prediction of interference path loss for A319/320 models through the integration of fuzzy logic and neural networks, and is currently developing an advanced deep learning system to quickly estimate the interference effect under different layouts by training neural networks.

Preliminary tests show that this method can reduce the computation time by 90% while achieving prediction accuracy equivalent to that of traditional CFD methods. In transonic aeroelastic prediction, similar technologies have achieved a high degree of consistency with the outcomes of CFD/CSD (Computational Structural Dynamics) coupling simulations. Nonetheless, the generalization capability of this method requires enhancement, while current models demonstrate stable performance with specific airfoils or flow conditions, the issue of inadequate generalization becomes more evident in complex interference scenarios involving various operating conditions. This necessitates further optimization through data assimilation and the incorporation of physical knowledge [8].

The application of bionics is an important breakthrough direction for multi-rotor system collaboration technology. Delft University of Technology (TU Delft, the Netherlands) has long been inspired by the local interaction mechanisms of swarms of insects, such as bees, and has focused on the research of autonomous collaboration in distributed multi-rotor systems. The core is to realize global intelligence through implicit rules between individuals rather than relying on centralized

control. Its publicly available experimental prototype is based on 33-gram micro-UAVs, with a typical swarm size of 6 units. Each unit integrates a 4-gram stereo vision system and a 2-gram autopilot, achieves centimeter-level positioning through Ultra-Wideband (UWB) technology, and adopts the REPATT chemotaxis algorithm to optimize swarm collaboration by broadcasting attraction/repulsion signals.

Experiments show that the swarm can explore 80% of the unknown space within 6 minutes and has significant redundancy—when a single UAV fails due to hardware problems, the remaining individuals can still complete the task. A prototype for formation flight with 20 rotor units has been reported in multi-rotor collaboration technology literature, but it has not been clearly identified as being developed under the leadership of TU Delft. Autonomous swarms of similar scales (such as Festo BionicBee) adopt technical ideas related to their positioning and control technologies. In theory, these bionic designs have the potential to prevent single-point failures by utilizing a distributed architecture; however, the current technology remains in the laboratory verification phase (Technology Readiness Level (TRL)3-4), and there is still a need to optimize environmental adaptability for large-scale swarms [9].

The adaptability of urban environments has garnered growing interest in research. With the rapid development of UAV applications in areas such as urban logistics and emergency rescue, complicated airflow and airspace barriers caused by dense buildings have become major problems restricting their safe operation. The Korea Aerospace Research Institute (KARI) has long studied urban UAV technology; its developed QTP series hybrid electric propulsion tiltrotor aircraft achieves the balance between vertical take-off and landing and high-speed cruising through rotor tilting, proving that dynamically adjusting rotor configurations can improve environmental adaptability.

In terms of technical breakthroughs, the Discrete Space Consensus Algorithm (DSCA) proposed by Wu et al. realizes the balance between obstacle avoidance and formation reconfiguration in dense buildings by optimizing the route coordination of UAV formations in real time. Its DSCA-IRRT fusion algorithm enables the formation to maintain more than 85% route safety in urban airspace. When studying closely spaced overlapping rotors, Xu et al. discovered the "slipstream-suction-induction" effect. By optimizing the shaft spacing (0.3-0.4 times the rotor diameter) and vertical blade spacing (0.1-0.12 times the rotor diameter), the size of the UAV is reduced by 20% while maintaining lift stability, providing a new rotor design idea for operations in narrow urban spaces [10].

4. Conclusion

Through a systematic review of existing research, it can be found that the four-rotor configuration remains the best choice in most conventional applications, while multi-rotor systems have unique advantages under special working circumstances. In the future, it is necessary to further solve key technical problems, such as inter-rotor interference prediction and system cooperative control, to promote the continuous improvement of UAV performance. Specifically, in the consumer-grade and light industrial application fields, four-rotor UAVs will continue to maintain their dominant position in the market in the next period due to their excellent energy efficiency ratio and mature industrial chain. With the development of battery technology and materials science, their performance still has space for further improvement; it is predicted that the endurance time of mainstream products will exceed 40 minutes within the next five years. In professional-grade and safety-critical application situations, the advantages of six-rotor systems are more obvious. Especially in fields such as power inspection and border patrol, their excellent reliability will continue to be favored by professional users. Future development directions may focus on intelligent fault diagnosis and autonomous emergency handling to further improve system safety. The heavy-load and special application fields will continue to rely on configurations with eight or more rotors. With the advancement of material lightweighting and power system optimization technologies, the energy efficiency ratio of such models is expected to be improved. At the same time, innovative designs such as changing rotor numbers may bring new development to this subject, which warrants constant attention. In general,

the selection of UAV rotor numbers needs to be completely examined based on particular application requirements, and there is no one-size-fits-all optimal solution. The characteristics of actual application situations should be given more attention in the future, which also creates more focused solutions, so that the application of multi-rotor UAV technology can be promoted in a more diversified and broad field.

References

- [1] ZHANG H L, QIAN J P, GUO C, et al. Analysis of Aerodynamic Interference Characteristics Between Rotors of the Multi-Rotor Suspension Device for Suspended Projectiles[J]. *Journal of Ordnance Equipment Engineering*, 2021, 42(7): 25-29.
- [2] ZHONGYAN PUHUA INDUSTRY RESEARCH INSTITUTE. 2025-2030 China UAV Industry Market In-Depth Research and Investment Strategy Forecast Report[R]. Shenzhen: Zhongyan Puhua, 2025.
- [3] CHINA ENERGY NETWORK. Eight-Rotor Heavy-Lift UAV Applied for the First Time in High-Altitude Construction in China[EB/OL]. (2024-05-22).
- [4] SHEN X Q, FAN J W, XUE T T, et al. Design and Simulation of Eight-Rotor UAV for Hybrid Control System[J]. *Computer Simulation*, 2018, 35(11): 38-44+55.
- [5] MERAGLIA S, GOZZINI G, LIU S, et al. Adaptive Control for High-Performance Trajectory Tracking of Multi-Rotor UAVs[C]//*Proceedings of the 9th International Conference on Control, Decision and Information Technologies*. Rome, Italy: IEEE, 2023: 1671-1676.
- [6] QYResearch. 2023-2029 Global and China Hydrogen Fuel Cell UAV Industry Research and 14th Five-Year Plan Analysis Report[R]. 2023.
- [7] WANG Z, WANG X, ZHANG W W, et al. ED-ResNet: Aerothermal Modeling and Prediction with Euler Equation-Embedded Stepwise Residual Neural Network[J]. *AIAA Journal*, 2024, 62(6): 2174-2185.
- [8] MCGUIRE K N, et al. Minimal navigation solution for a swarm of tiny flying robots to explore an unknown environment[J]. *Science Robotics*, 2019, 4: eaaw9710.
- [9] WU Y, LOW K H. Discrete space-based route planning for rotary-wing UAV formation in urban environments[J]. *ISA Transactions*, 2022, 129: 243-259.
- [10] KARI. KARI Hybrid-Electric Rotorcraft (concept design)[EB/OL]. (2023-12-09). <https://www.evtol.news/kari-hybrid-electric-rotorcraft>.