

Review of the Key Technology System for Low-Altitude Aircraft

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Abstract: Low-altitude aircraft are the physical carriers through which the low-altitude economy moves from concept to scaled operation. Taking electric vertical take-off and landing (eVTOL) aircraft as its core object, this paper systematically reviews the research progress and bottlenecks of their key technology system. After briefly tracing the trajectory of technological evolution, the paper analyzes five dimensions: overall aerodynamic configuration, distributed electric propulsion, energy supply and management, intelligent autonomous flight, and low-altitude traffic management. The study finds that tilt configurations account for the highest proportion of global product designs and are gaining relatively unified recognition; the core contradiction of electric propulsion systems is shifting from "whether it can fly" to "the synergistic optimization of power density and thermal management," with high torque density and power density becoming the central pursuit of motor design; the physical constraints on battery energy density persist, and hybrid energy architectures are attracting increasing attention; conflict detection and resolution (CDR) methods can be grouped into two major categories—classical rule-based methods and learning-based methods; and consensus is forming on the status of low-altitude route maps as a new type of public infrastructure. This paper argues that low-altitude aircraft technology is currently in a critical window of transition from prototype validation to airworthiness operations, and that the construction of a system-level safety governance framework will become the core variable determining the scaled deployment of the technology.

Keywords: low-altitude aircraft; eVTOL; distributed electric propulsion; low-altitude traffic management; airworthiness safety

1. Introduction

As a comprehensive economic form relying on low-altitude airspace and driven by various low-altitude flight activities, the low-altitude economy has recently attracted dual attention from policy and capital worldwide. In this industrial landscape, low-altitude aircraft constitute the most fundamental technological layer—without safe, efficient, and scalable flight platforms, route networks, operational services, and business models would all be impossible.

The technological spectrum of low-altitude aircraft is quite broad, covering a complete range from micro multirotor drones to medium-sized logistics drones and further to manned electric vertical take-off and landing (eVTOL) aircraft. Among these, eVTOL, owing to its pivotal role in urban air mobility (UAM), has become the technical direction attracting the most concentrated attention from both academia and industry. The concept of eVTOL can be traced back to vertical take-off and landing demonstrator aircraft in the mid-20th century, but what truly endowed this configuration with practical feasibility was the cross-maturation of three technologies: distributed electric propulsion, high-energy-density batteries, and intelligent flight control. According to industry statistics, more than 350 eVTOL-related companies have emerged globally, and investment in this field reached approximately USD 5.8 billion in 2021 alone, reflecting strong market confidence in the prospects of urban air mobility.

However, rising technological enthusiasm does not equate to the resolution of technological bottlenecks. In their systematic review of the development history of eVTOL in the context of the low-altitude economy, Meng et al. pointed out that flight performance metrics, overall aerodynamic configuration, distributed electric propulsion systems, long-endurance battery technology, intelligent autonomous flight, digital low-altitude traffic management systems, and airworthiness and safety assurance constitute the concentrated areas of current

technological bottlenecks. This paper aims to sort out and evaluate these dimensions, analyzing their current levels, principal contradictions, and development trends.

2. Overall Aerodynamic Configuration and Platform Design

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2.1 Configuration Spectrum and Design Trade-offs

The overall configuration choice of low-altitude aircraft fundamentally determines their flight performance envelope, operational scenario adaptability, and airworthiness verification difficulty. Current mainstream eVTOL configurations can be grouped into three categories: multirotor, compound-wing, and tilt-duct (tiltrotor) configurations.

The multirotor configuration features a simple structure, high hover efficiency, good control redundancy, and relatively low technical risk and development difficulty, but it suffers from small payload, low flight speed, and short range, making it mainly suitable for short-distance urban scenarios such as emergency rescue and low-altitude sightseeing. The compound-wing configuration spatially separates rotors from fixed wings, which respectively handle vertical take-off and landing and cruise functions, thereby avoiding the complexity of tilt mechanisms. Its development cycle is shorter, production and maintenance are simpler, and its airworthiness path and means of compliance are more readily accepted by regulators, but the cost is that the rotor system, which is useless during cruise, must be carried aloft, resulting in a low payload ratio and relatively high cost. The tilt-duct (tiltrotor) configuration achieves shared propulsion between vertical take-off and landing and cruise, offering lighter weight, high thrust, high flight speed, and markedly improved range and payload; in theory it has the optimal overall efficiency, but its development is technically difficult and costly, and the flight-

control complexity and structural reliability requirements of the tilt-transition phase constitute significant technical thresholds.

In terms of the global distribution of product designs, tilt configurations rank first with 350 products, followed by multirotor configurations with 284 and compound-wing configurations with 172, and tiltrotors dominate in recent product designs, indicating that tilt configurations are gaining relatively unified industry recognition. Domestically, the AE200 from Aerofugia and the E20 from TCab Tech have reached the same order of magnitude as international leading products such as Joby in terms of range, speed, and payload, but their airworthiness certification progress lags by approximately one to three years.

2.2 From Performance Metrics to Scenario Adaptability

One noteworthy trend is that the evaluation criteria for configuration design are shifting from single flight performance metrics to "scenario adaptability"—that is, the degree of match between the flight platform and a specific operational scenario. Multirotor configurations suit short-distance intra-city scenarios, compound-wing configurations suit intra-city or inter-city transportation, and tiltrotor configurations target longer-distance scenario requirements such as inter-city or urban transportation operations and logistics. This scenario-driven design philosophy implies that there is no universally "optimal configuration," only a suitable configuration that matches scenario constraints and operational economics. In addition, analyses based on patent data indicate that the technological development trends and patent layout strategies of manned eVTOL are attracting increasing attention, reflecting that technological competition is extending from the product level to the intellectual property level.

3. Active Suspension System Control Methods

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3.1 Architectural Advantages and Costs of Distributed Electric Propulsion

Distributed electric propulsion (DEP) is one of the most core technical features distinguishing eVTOL from conventional helicopters. By distributing multiple electric ducted fans or propellers around the wings or fuselage, DEP brings several capabilities difficult to achieve with conventional power systems: thrust vectors can be realized through differential control, thereby reducing reliance on complex mechanical transmissions and variable-pitch mechanisms; multi-motor redundancy ensures that a single-point failure will not lead to catastrophic consequences; and the flexibility of motor size provides greater scope for aerodynamic-propulsive integrated design.

In a review published in *Acta Aeronautica et Astronautica Sinica*, Miao Yongze et al. systematically expounded the different architectures of eVTOL electric drive systems, organized and summarized major eVTOL products at home and abroad and the electric drive systems they adopt, analyzed the performance metrics and technical characteristics of each electric drive system, and clarified the current state of the art. The study further explored research progress in eVTOL motors regarding electromagnetic, cooling, structural and material, and electronic control design, pointing out that high

torque density and power density are the central pursuit of current motor design.

3.2 Definition of Electric Propulsion under the Airworthiness Framework

In its powered-lift certification framework, the FAA defines the complete electric propulsion unit, including the motor and its driver, as an "electric engine"; this term is clarified under advisory circular AC 21.17-4, providing an institutional basis for airworthiness assessment of eVTOL electric propulsion systems. This classification means that electric propulsion systems must be reviewed against airworthiness standards comparable to those for aircraft engines, covering dimensions such as thermal performance, redundancy management, electromagnetic compatibility, and failure modes. A review study of eVTOL propulsion units further points out that the choice between axial-flux and radial-flux motors, the trade-off between air cooling and liquid cooling designs, and the comparison of different redundancy strategies constitute the core engineering decisions in current electric propulsion system integration, and these decisions directly affect efficiency, power density, and manufacturability.

4. Energy Supply: Batteries, Hybrid Architectures, and Management Strategies

4.1 Realistic Constraints of Energy Density

Batteries are the primary physical constraint on the performance boundary of eVTOL. The specific energy of current lithium-ion batteries is on the order of 250–300 Wh/kg, whereas the specific energy of aviation kerosene is approximately 12,000 Wh/kg—an order-of-magnitude gap. This gap means that purely electric eVTOL aircraft are inherently unable to compete with fuel-powered aircraft in range and payload. The positioning of eVTOL has never been to replace regional airliners, but to fill the short-distance gap between ground transportation and air transport.

Nevertheless, battery technology remains a core variable in the operational economics of eVTOL. The high power demand during vertical take-off and landing requires batteries with high-rate discharge capability, and high rates often come at the expense of energy density and cycle life. How to strike a balance between power density and energy density is the core issue in battery selection. Related studies have systematically analyzed the power system composition and energy management strategies of eVTOL aircraft, focusing on key technologies such as electric motors, batteries, hybrid power, and fuel cells, as well as energy recovery strategies.

4.2 Hybrid Energy Architectures and Alternative Routes

Against the backdrop of slowing improvements in battery energy density, hybrid energy systems are receiving increasing attention. One approach combines high-energy-density batteries with high-power-density energy storage devices, with the latter bearing the high-power impact during take-off and landing. Another approach adopts a hybrid electric propulsion architecture, using a small turbogenerator as a range extender. In addition, hydrogen fuel cells, as a potential alternative route, have also entered the research horizon: the specific energy of hydrogen is approximately 33 kWh/kg, and refueling typically takes no more than 10 minutes, but the power density of fuel cell systems is low (about 1–2 kW/kg) and membrane durability is limited, while

the lack of hydrogen refueling infrastructure also constitutes a significant obstacle.

5. Intelligent Autonomous Flight and Low-Altitude Traffic Management

5.1 Two Paradigms of Conflict Detection and Resolution

Large-scale operations of low-altitude aircraft cannot rely on the current air traffic control model. The unmanned aircraft system traffic management (UTM) system was originally designed precisely to achieve orderly operation of unmanned aerial vehicles in low-altitude airspace. In a review published in IEEE Transactions on Intelligent Transportation Systems, Hamissi et al. systematically reviewed research progress on conflict detection and resolution (CDR) methods in UTM, explicitly dividing existing methods into two major categories: classical (non-learning) methods and learning-based methods.

Classical methods typically rely on predefined algorithms or rules to guide drones in avoiding collisions, offering advantages in interpretability and ease of verification, but their scalability in high-density, highly dynamic scenarios is limited. Artificial intelligence-based methods, especially machine learning (ML) and reinforcement learning (RL), enable drones to adapt to the environment, autonomously resolve conflicts, and exhibit intelligent behavior based on experience, showing greater potential in adaptability, but they face the challenge of generalization risk between training distributions and actual operating scenarios. The review also discusses the challenges and issues faced by various methods, providing a foundational reference resource for the selection of conflict resolution methods in UTM systems.

5.2 Systematic Requirements of Low-Altitude Traffic Management

Meng et al.'s review explicitly lists digital low-altitude traffic management systems as one of the core technical dimensions of eVTOL, alongside flight performance, aerodynamic configuration, electric propulsion, and battery technology. This classification itself indicates that low-altitude traffic management has risen from an ancillary issue at the operational level to an architectural issue of equal importance to the technical system. The planning and management of low-altitude routes are moving from "each company planning its own" toward a public infrastructure model, in which basic surveying and mapping data provide a unified foundation and operating companies feed back local changes during flight; if this combined update mechanism can be implemented, it will significantly reduce the repetitive infrastructure costs of low-altitude operations. Embedding governance rules such as capacity, separation, and right-of-way into route design and system architecture, rather than treating them as additional requirements of ex post supervision, is becoming a design principle of low-altitude traffic management.

6. Conclusion

Low-altitude aircraft technology is at a delicate historical juncture. From the perspective of technological maturity, the

main problems of the prototype validation stage have largely been solved; but from the perspective of airworthiness operations, the real difficulties are just emerging. Thermal management and power density of electric propulsion systems, the energy boundary of batteries, the verifiability of autonomous decision-making, and the infrastructuralization of low-altitude routes—the solutions to these problems do not depend on any single "disruptive breakthrough," but rather require system-level synergistic optimization and engineering iteration.

The fact that tilt configurations have gained relatively unified industry recognition indicates that technological routes are converging, but the lag in airworthiness certification—a one-to-three-year certification progress gap between leading domestic products and international benchmarks such as Joby—suggests that engineering capability and standard-setting influence may become more critical competitive dimensions than the technology itself. The scaled operation of eVTOL is more likely to be realized first in environments with constrained scenarios and controllable risks, such as airport shuttles, island transportation, and medical emergency services on fixed routes. The commercial validation of these scenarios will provide real data for technological iteration and practical evidence for the improvement of airworthiness standards and safety governance rules. From "being able to fly" to "being able to operate," low-altitude aircraft still have a not insignificant path to complete.

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