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A Review of Lightweight Methods for Unmanned Aerial Vehicles

Jie Ma

School of Energy and Mechanical Engineering,Dezhou University, Dezhou, Shandong, 253023, China

ABSTRACT

This study focuses on lightweight technology for unmanned aerial vehicles (UAVs), aiming to systematically review research progress and technical bottlenecks in this field while identifying future development directions to provide a technical framework for subsequent research. Based on highly cited literature from multiple platforms spanning 2015–2025, an analytical framework was constructed from three major dimensions: material technology, structural design, and system integration. Lightweight methods and their application effectiveness across these dimensions were reviewed. The study reveals that UAV lightweighting has achieved technological breakthroughs in multiple aspects: advanced lightweight materials enable 30% – 50% weight reduction, topology optimization and bionic design effectively enhance structural efficiency, while the miniaturization and integration of power and sensor systems significantly reduce overall weight. However, current research still faces challenges such as insufficient cross-scale collaborative design, preliminary integration of smart materials, and a lack of full life-cycle assessment systems. Shortcomings also exist in extreme environment adaptability, balancing lightweighting with functional performance, and cost control. Future research should emphasize multi-scale coupled design, promote deeper integration of smart materials and bionic structures, establish a full life-cycle weight reduction assessment framework, and achieve both technological breakthroughs and sustainable development.

KEYWORDS

UAV lightweighting; Advanced lightweight materials; Topology optimization; Structural design; System integration

1 Introduction

1.1 Research Background and Significance

Drone lightweighting has emerged as a core direction in current UAV technological development, playing an irreplaceable role in enhancing flight endurance, payload efficiency, and maneuverability. With the expanding applications of drones in military reconnaissance, civilian mapping, and logistics transportation, traditional structures and material systems struggle to meet the demands for long endurance, high payload capacity, and high mobility. For instance, a 10% reduction in airframe weight can extend flight time by approximately 15% and increase payload capacity by over 8%—data that directly underscores the critical impact of lightweighting on UAV performance. This literature review focuses on three technical dimensions: material technology, structural design, and system integration, explicitly delimiting industrial and consumer drones as primary application scenarios. It aims to systematically outline research progress and technological bottlenecks in the field of lightweighting.

Topology optimization, as a key method for structural lightweight design, achieves optimal material distribution in space through algorithmic iterations, enabling a 30% to 50% reduction in redundant weight while maintaining structural strength. To realize lightweight-oriented topology optimization, additive manufacturing technologies must be integrated to translate complex optimized structures into functional parts—for instance, topology-optimized drone fuselage components fabricated via Selective Laser Melting (SLM) technology exhibit a 42% weight reduction compared to traditionally milled parts, alongside an 18% improvement in torsional stiffness [1]. This technological synergy not only overcomes the limitations of conventional manufacturing processes but also opens new pathways for lightweight design and functional integration in drone structures.

The significance of lightweight drone research extends beyond performance enhancement to promoting the sustainable development of the drone industry. Lightweight design reduces drones' reliance on power systems, decreasing energy consumption and carbon emissions—estimates indicate that lightweight drones can lower energy consumption per mission by 20% to 30%, aligning with industry trends toward green manufacturing and low-carbon development. Meanwhile, breakthroughs in lightweight technology will further expand drones' application scenarios, such as in extreme environments like high-altitude regions and long-distance inspections, where the advantages of lightweight drones become more pronounced. This paper provides a systematic review of lightweight technologies, offering a clear technical framework and directional guidance for future research.

1.2 Literature Retrieval and Analysis Framework

The literature search for this study primarily focused on highly cited and top-tier journal publications from the past decade (2015–2025), aiming to capture cutting-edge research outcomes and track the technological evolution in the field of drone lightweight design. Data were sourced from internationally authoritative databases such as IEEE Xplore, ScienceDirect, and Web of Science, supplemented by Chinese core literature related to drone structural optimization from the China National Knowledge Infrastructure (CNKI). This approach ensured comprehensive coverage of multidimensional

research advancements in materials, structural design, and integration technologies.

The literature analysis framework revolves around three core aspects of UAV lightweighting: the first aspect is material technology, focusing on the performance parameters and application scenarios of advanced lightweight materials (such as carbon fiber composites, magnesium-lithium alloys, ceramic matrix composites, etc.); the second aspect is structural design, systematically summarizing the impact of methods like topology optimization, bionic structures, and modular design on structural weight reduction efficiency; the third aspect is system integration technology, analyzing lightweight integration strategies for subsystems such as power systems and sensor payloads. Through the logical chain of "materials-structure-integration," this framework achieves a comprehensive deconstruction of the UAV lightweighting technology system.

During the literature screening process, studies in the field of structural design that employed simulation-based optimization methods were prioritized for inclusion. Examples include wing structure weight reduction designs utilizing finite element analysis, where multi-objective optimization algorithms balance structural strength and weight, providing quantifiable technical pathways for UAV lightweighting [2]. Through this retrieval and analytical framework, the study effectively highlights research hotspots and technological gaps in UAV lightweighting, laying a foundation for the subsequent review and outlook sections.

2 Review of Material Technology Research for Lightweight UAVs

2.1 Research on Advanced Lightweight Materials Applications

Advanced lightweight materials are the core enabler for drone lightweighting design, and their application directly impacts payload capacity, endurance, and flight performance. Carbon fiber reinforced polymer (CFRP), with its high specific strength (approximately 5 times that of steel and 3 times that of aluminum alloy) and low density, has become the preferred material for primary load-bearing structures in drones (e.g., airframe frames, wing skins). Its forming processes, such as prepreg compression molding and resin transfer molding (RTM), achieve 30%-50% weight reduction while ensuring structural integrity. Magnesium/aluminum alloys, as traditional lightweight metals, remain widely used in non-load-bearing components (e.g., landing gear, connection brackets) due to their excellent formability and cost advantages. Magnesium alloys offer a specific strength of 140-160 MPa·cm^3/g, while aluminum alloys provide superior corrosion resistance and machining efficiency. Emerging nanomaterials (e.g., carbon nanotube-reinforced composites, graphene-based materials) further enhance material properties through microstructure tailoring. For instance, carbon nanotube doping can increase tensile strength by 20%-30%. However, due to high production costs and immature large-scale application technologies, these materials remain primarily in the laboratory research stage.

There are significant differences in the performance, processing techniques, and cost-effectiveness of various lightweight materials, requiring selection based on the application scenarios and design requirements of drones. Although carbon fiber composites offer excellent performance, their raw material cost is approximately 5-8 times that of aluminum alloys, and their molding cycle is longer, making them suitable for high-end drones that are weight-sensitive (such as reconnaissance drones and long-endurance drones). Magnesium/aluminum alloys cost only 1/10 to 1/5 of carbon fiber composites, with mature processing techniques, making them suitable for mass-produced small and medium-sized drones (such as consumer-grade drones and agricultural drones). Nanoreinforced materials are even more expensive, and their molding process requires precise control of nanoparticle dispersion. Currently, they are only being experimentally applied in key components of specific high-performance drones.

The application of advanced lightweight materials must integrate structural design and manufacturing processes to achieve a balance between lightweight performance and functionality. Topology optimization technology can be combined with lightweight materials to further reduce weight by eliminating redundant structures. For example, in the structural design of agricultural drone airframes, the integration of carbon fiber composites and topology optimization can reduce structural weight by 25% while maintaining load-bearing capacity [3]. Additive manufacturing technology enables the forming of complex lightweight structures, such as 3D printing of magnesium alloys for integrated structure manufacturing, which reduces weight loss from assembly processes. In the future, the development of lightweight materials will focus on low-cost preparation techniques, multi-material integrated forming, and dynamic regulation of material properties to meet the diverse lightweight requirements of drones.

2.2 Research on Material Performance Optimization

Optimizing material properties is the core approach to achieving a balance between lightweight design and mechanical performance in drones. Scholars have conducted systematic research on technologies such as material interface modification and reinforcement phase doping. Interface modification technology addresses the mechanical performance limitations caused by poor interfacial compatibility in traditional composite materials by regulating the bonding state between the matrix and the reinforcement phase. For instance, treating carbon fiber surfaces with coupling agents can increase the interlaminar shear strength of composites by more than 20% while maintaining material density below 1.6 g/cm^3 [4]. Reinforcement phase doping involves introducing nanoscale reinforcing particles (such as carbon

nanotubes or graphene) into the matrix, enabling simultaneous improvements in tensile strength and modulus without significantly increasing material density. Some studies show that doping with 0.5% mass fraction of graphene can enhance the tensile strength of composites by 15% and flexural modulus by 12%.

The impact mechanism of material performance optimization technology on weight reduction in UAV structures is manifested through multidimensional synergistic performance enhancements. Interface modification improves interfacial bonding strength, reducing stress concentration caused by interface defects, which leads to a more uniform mechanical response of the material under aerodynamic loads. This allows for an appropriate reduction in material thickness in structural design, achieving a weight reduction of 10% – 15%. Reinforcement phase doping, through the strengthening effect of nanoparticles, enhances the specific strength and specific modulus of the material, providing a material foundation for the lightweight design of key UAV structural components (such as wing skins and fuselage frames) [4]. For example, a certain UAV model utilizing carbon fiber composite wings with interface modification achieved a 25% reduction in structural weight compared to traditional aluminum alloy wings while maintaining the same load-bearing capacity, effectively improving the UAV's endurance and payload capacity.

The core objective of materials performance optimization research is to achieve a dynamic balance between weight reduction efficiency and mechanical properties, which directly impacts the flight performance and mission adaptability of unmanned aerial vehicles (UAVs). In current studies, the combined application of interface modification and reinforcement phase doping technology has emerged as a new trend. By synergistically regulating interface properties and reinforcement phase distribution, the comprehensive performance of materials can be further optimized. For instance, combining silane coupling agent modification with carbon nanotube doping can increase the specific strength of composite materials to 350 MPa·cm^3/g, representing an approximately 18% improvement compared to single modification techniques [4]. In the future, optimization research focusing on material performance stability under extreme environments (such as high-low temperature cycling and humid-heat conditions) will become a critical direction for transitioning materials performance optimization technologies to engineering applications, addressing the lightweight requirements of UAVs in complex mission scenarios.

3 Research Progress in Lightweight Structural Design of Unmanned Aerial Vehicles

3.1 Topology Optimization and Bionic Structural Design

Topology optimization algorithms are the core technical means for lightweight structural design in unmanned aerial vehicles, with the Solid Isotropic Material with Penalization (SIMP) method and level set method being the most widely applied for weight reduction in fuselages and wings. The SIMP algorithm achieves optimal material distribution within the structural space through continuous interpolation and penalization of element material density, reducing redundant material by 30%-40% while maintaining structural strength. The level set method describes the evolution of structural boundaries via implicit functions, more accurately capturing topological configurations under complex loading conditions, making it particularly suitable for components with aerodynamic constraints such as wings. Bio-inspired structural design serves as a crucial supplement to topology optimization, deriving its logic from mimicking the efficient mechanical properties of natural structures: honeycomb structures, leveraging the uniform strength distribution of hexagonal units, enhance structural stiffness by over 25% at identical weights; the hollow 网状 structure of avian bones achieves a balance between strength and lightweight through rational internal truss arrangement. Related bio-inspired designs have demonstrated 15%-20% weight reduction in small UAV fuselage frameworks.

The integrated design of structure and material based on variable cross-section layup is a typical practice combining topology optimization with bionic principles. This method builds upon the material distribution determined by topology optimization and adjusts the thickness, angle, and sequence of composite material layups to precisely match the mechanical properties of different structural regions with their load requirements. It not only retains the lightweight potential of topology optimization but also further enhances structural efficiency by leveraging material anisotropy [5]. For example, in UAV wing design, using high-modulus carbon fiber unidirectional layups in the main load-bearing areas identified through topology optimization, while employing hybrid fiber woven layups in secondary areas, can achieve a 28% reduction in overall weight compared to traditional designs without compromising aerodynamic performance.

The synergistic application of topology optimization and bionic structural design provides a complete technical pathway from theory to practice for the lightweighting of unmanned aerial vehicles (UAVs). Topology optimization employs mathematical models to achieve "optimal morphology generation" of structures, resolving the conflict between strength and weight reduction that is difficult to address in traditional empirical designs. Bionic structures, by drawing inspiration from natural evolutionary principles, offer engineering-ready structural paradigms for topology optimization outcomes. The integration of these two approaches not only enhances the efficiency of UAV structural weight reduction but also lays the foundation for future multidisciplinary-coupled lightweight design. This is particularly evident in weight-sensitive models such as long-endurance UAVs and micro-UAVs, where it demonstrates significant application value.

3.2 Modular and Integrated Design

Modular and integrated design is one of the core approaches to achieving lightweight drones. It effectively reduces redundant structures and enhances spatial utilization through the modular division of components and the integration of structure and function. Modular design breaks down the drone into independent functional modules (such as the power module, flight control module, and payload module). Each module can be quickly assembled and maintained via standardized interfaces, while avoiding repetitive support and connection components found in traditional decentralized structures. On the other hand, structure-function integration combines load-bearing structures with functional elements (such as cooling channels and wiring slots). For example, integrating the fuselage frame with the battery compartment and antenna base reduces the weight of additional attachments while meeting structural strength requirements.

Different integration schemes present significant trade-offs between assembly efficiency and weight reduction. Modular design offers high assembly flexibility, where a fault in a single module only requires replacement of the corresponding unit. For instance, a certain multirotor drone reduced assembly time by 40% after adopting a modular propulsion system, though interface structures between modules introduced some weight redundancy. In contrast, integrated design achieves better weight reduction by minimizing the number of interfaces. A specific fixed-wing drone's integrated fuselage-wing structure, for example, achieved a 15% weight reduction compared to traditional riveted structures. However, this approach increases overall manufacturing complexity and necessitates full disassembly for repairs, thereby reducing maintenance efficiency.

Topology optimization technology provides quantitative support for modular and integrated design approaches, by algorithmically optimizing material distribution to maximize weight reduction potential while ensuring structural performance. Li Heng et al. demonstrated this through a case study on a quadrotor drone fuselage, employing topology optimization to co-design a modular framework and an integrated payload bay. Under the constraints of modal frequency and strength requirements, they achieved a 22% reduction in fuselage structural weight. Concurrently, topology optimization of modular interfaces mitigated stress concentration at connection points, balancing assembly convenience with structural lightweight objectives [6]. This study indicates that integrating topology optimization with holistic design can effectively harmonize assembly efficiency and weight reduction, offering a viable technical pathway for lightweight drone design.

4 Research on System Integration Technology for Lightweight UAVs

4.1 Lightweight Powertrain System Research

The lightweight design of power systems is a core aspect of reducing the overall weight of unmanned aerial vehicles (UAVs). Research in this field focuses on three main directions: high-energy-density batteries, miniaturized motors, and efficient power transmission systems. In the area of high-energy-density batteries, the development of new energy storage technologies such as lithium-sulfur batteries and solid-state batteries has significantly increased energy output per unit mass. Some laboratory prototypes have achieved energy densities exceeding 500Wh/kg, approximately doubling that of traditional lithium-ion batteries. For miniaturized motors, the use of rare-earth permanent magnet materials and optimized winding structures has enabled a reduction in volume and mass by over 30% while maintaining output power. Efficient power transmission systems, through gear parameter optimization and integrated design, reduce transmission losses while achieving structural weight reduction, with some solutions achieving transmission efficiencies of over 95%. The contribution of different power solutions to overall weight reduction varies, with high-energy-density batteries accounting for approximately 40%, miniaturized motors and transmission systems contributing 30% and 20% respectively, and the remaining 10% coming from system integration optimization.

Carbon fiber composites play a critical role in the lightweighting of power systems. Their low density (approximately 1.7 g/cm^3) and high strength (tensile strength can exceed 3000 MPa) effectively reduce the mass of battery enclosures, motor housings, and transmission components. For example, drone battery enclosures made of carbon fiber composites are more than 50% lighter than those made of aluminum alloy, while meeting structural strength requirements for vibration and impact resistance [7]. Furthermore, the application of this material in motor stator frames and transmission gears further enables the lightweight integration of power systems, providing material support for overall weight reduction of the entire machine.

Research trends in powertrain lightweighting are characterized by multi-technology integration. The collaborative design of high-energy-density batteries and miniaturized motors enhances overall system efficiency through voltage and power matching while reducing redundant components. The integration of efficient power transmission systems with carbon fiber composites further optimizes structural layout and mass distribution. Future research should focus on the holistic integration of powertrain components, employing multidisciplinary optimization methods to balance energy density, power output, and structural lightweighting, thereby providing technical support for long-endurance and high-payload applications of unmanned aerial vehicles.

4.2 Lightweight Integration of Sensors and Payloads

The lightweight integration of sensors and payloads is one of the core aspects of UAV system lightweighting. Its key lies in achieving effective weight reduction while maintaining functional integrity through the development of miniaturized sensors and the design of integrated avionics systems. Significant progress has been made in miniaturized sensor technology; for example, MEMS (Micro-Electro-Mechanical Systems) sensors have reduced in volume by over 60% compared to traditional sensors, with weights dropping below 10g, while still maintaining high-precision environmental sensing capabilities. Integrated avionics systems, by combining hardware integration and software fusion of modules such as flight control, navigation, and communication, reduce redundant components, leading to a total system weight reduction of approximately 35% [8]. These technological achievements provide critical support for the lightweighting of UAV payload systems.

The development of miniaturized sensors focuses on material selection and structural optimization, employing lightweight materials such as ceramic-based and polymer-based composites to replace traditional metal casings. Combined with micro-fabrication techniques, the core components of sensors are miniaturized while maintaining sensitivity and stability, further reducing volume and weight. For integrated avionics systems, weight reduction is achieved through architectural design by adopting modular integration solutions. Multiple functional modules are consolidated into a single hardware platform, reducing the use of auxiliary components such as connectors and cables. Simultaneously, software algorithms are optimized to decrease hardware resource demands, accomplishing system-level lightweight objectives [8].

In balancing functional completeness and lightweight design, sensor and payload integration requires the establishment of an optimization model under multiple performance constraints. For instance, in the development of miniaturized sensors, simulation analysis is necessary to verify performance stability under complex environmental conditions such as vibration and temperature, ensuring that weight-reduced sensors still meet the mission requirements of unmanned aerial vehicles (UAVs). Integrated avionics systems, on the other hand, must employ redundancy design and fault-tolerant algorithms to reduce hardware quantity while maintaining system reliability. The multi-objective optimization method proposed by Guo Xuewei in the study of composite material UAV structural optimization offers a valuable technical approach for the lightweight design of sensor and payload integration. This approach involves establishing a collaborative optimization model for weight, performance, and cost to achieve enhanced overall system performance [8].

The development trend of sensor and payload lightweight integration technology is evolving towards higher integration and superior performance. Future research needs to further break through the performance limits of miniaturized sensors and develop new sensor components with low power consumption and high integration. Simultaneously, efforts should be made to advance the intelligent design of integrated avionics systems, optimizing resource allocation through artificial intelligence algorithms. This approach will enhance the autonomous perception and mission execution capabilities of unmanned aerial vehicles while achieving extreme lightweighting. Continued exploration in this direction will provide critical technological support for the overall lightweighting of UAV systems.

5 Research Summary and Future Outlook

5.1 Review of Existing Research

Current lightweight research on unmanned aerial vehicles (UAVs) has achieved multidimensional technological breakthroughs at the material, structural, and system levels. At the material level, the application of advanced lightweight materials such as carbon fiber reinforced polymer (CFRP) and basalt fiber has reduced the weight of UAV structural components by 30%–50% compared to traditional metal materials, with CFRP accounting for over 60% of fuselage skins and wing structures. In structural design, topology optimization technology enables precise control of material distribution through finite element analysis, while the introduction of biomimetic structures (e.g., honeycomb structures, avian bone structures) further enhances specific strength. For instance, a small reconnaissance UAV achieved a 25% increase in stiffness and an 18% reduction in weight after adopting biomimetic wings. At the system integration level, lightweight efforts for power systems focus on developing high-energy-density batteries and miniaturized motors, whereas sensor payloads are compressed in size through chip integration and modular design. The integration level of the flight control system in a consumer-grade UAV has improved by 40% compared to five years ago, with a 35% reduction in weight.

Current research has reached a preliminary consensus on the synergistic optimization of lightweight technologies: the potential of any single technology faces inherent limitations, necessitating cross-level collaboration among materials, structures, and systems to achieve comprehensive weight reduction. For instance, an industrial-grade drone combining CFRP materials with topology-optimized structures achieved a 22% reduction in overall weight while extending flight endurance by 30%. However, debates persist regarding the technical pathways for synergistic optimization. Some studies advocate for prioritizing material performance enhancement, arguing that high-modulus fiber materials can reduce

structural design complexity. Others emphasize the dominant role of structural topology, contending that rational structural layouts can compensate for material deficiencies. Additionally, significant gaps remain in extreme environment adaptability. Existing lightweight technologies still fail to effectively address performance degradation under extreme conditions such as high temperature, high humidity, and strong vibrations. For example, a high-altitude operational drone experienced a 15%-20% decline in the mechanical properties of lightweight materials at altitudes above 4,000 meters, compromising flight stability.

The limitations of current research are also evident in the balance between lightweight design and functional performance. Most studies excessively focus on weight reduction while inadequately addressing core functionalities such as payload capacity and fatigue resistance. For instance, a drone with a lightweight design achieved a 25% weight reduction, but its wing fatigue life decreased by 30%, making it difficult to meet long-term operational demands. Meanwhile, research on cost control for lightweight technologies lags behind, as the application of advanced lightweight materials and complex structural designs increases manufacturing costs by 2-3 times, limiting the large-scale adoption of these technologies. These issues highlight future directions for drone lightweighting research, emphasizing the need to seek a better balance among multi-technology integration, adaptability to extreme environments, and cost control.

5.2 Research Limitations and Future Prospects

Current research on drone lightweighting has achieved phased progress in single-scale optimization (e.g., material microstructure or structural macro-configuration), yet systematic studies on cross-scale collaborative design remain insufficient. Existing research predominantly focuses on density reduction at the material level or topological optimization at the structural level, lacking in-depth exploration of the coupling mechanisms between microscopic material properties, mesoscopic structural configurations, and macroscopic system integration. This gap results in lightweight solutions struggling to achieve synergistic improvements in performance and weight reduction across multiple scales. The integration of smart materials and structures remains in its nascent stage. The incorporation of smart materials such as shape memory alloys and piezoelectric ceramics into drone structures is largely confined to single-function applications (e.g., adaptive deformation). A holistic design paradigm that integrates materials, structures, and functionalities has yet to be established, limiting the full exploitation of smart materials' potential for weight reduction and performance modulation under dynamic loads.

The absence of a comprehensive life-cycle weight reduction evaluation system limits the practical application value of lightweight solutions. Current research predominantly focuses on static weight reduction outcomes during the design phase, while insufficient attention is given to assessing weight reduction benefits across the entire lifecycle. This includes material loss during manufacturing, structural fatigue degradation in service, and post-retirement recycling. Consequently, some lightweight designs achieve theoretical weight reduction but fail to effectively control actual lifecycle costs and environmental impacts. Future research on drone lightweighting should strengthen cross-scale collaborative design methodologies, establishing multi-scale coupling models that integrate material modifications at the atomic level with system-scale integration. It is essential to promote the deep integration of smart materials and bio-inspired structures, developing intelligent structural systems that combine adaptive functionality with lightweight characteristics. A full lifecycle weight reduction assessment framework must be established, incorporating weight-saving benefits from manufacturing, service, and recycling phases into design decisions to achieve technological breakthroughs and sustainable development in drone lightweighting.

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