UAV Wing Structure: Status and Future Trend

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Abstract. Unmanned Aerial Vehicles (UAVs) have emerged as a critical technological component with widespread applications in military reconnaissance, civil logistics, medical delivery, and environmental monitoring, with technological advancements fundamentally dependent on continuous innovations in structural design, materials science, and electronic integration. Structural design, serving as the core of UAV technology, directly determines flight performance, mission adaptability, and operational lifespan, and this comprehensive review systematically examines fundamental design principles, analyzing fixed-wing, rotary-wing, and hybrid configurations while exploring innovative approaches such as lightweight technologies, modular design, and biomimetic strategies. By critically evaluating the current challenges including payload limitations, wind resistance, regulatory constraints, and the delicate balance between durability and cost, the research illuminates the trajectory of UAV structural design towards intelligent, lightweight, and sustainable development, emphasizing the potential for interdisciplinary breakthroughs in urban air mobility, deep space exploration, and swarm mission capabilities that will ultimately promote the global technological accessibility and the sustainable advancement.

Keywords: UAV, Fixed-Wing, Rotary-Wing, Hybrid Configuration

1 Introduction

Driven by technological advancements, unmanned aerial vehicles (UAVs) have expanded from military reconnaissance tools to multidisciplinary applications including agriculture, logistics, environmental monitoring, and rescue operations, progressively highlighting their critical significance. This development fundamentally relies on breakthrough innovations in structural design, materials science, and electronic integration. Structural design, serving as the core technological element, directly influences flight performance, mission adaptability, and operational lifespan, necessitating optimization based on specific application scenarios to determine weight, stability, and efficiency. The introduction of intelligent technologies further propels UAVs towards more efficient and multifunctional evolution. This study comprehensively explores the fundamental principles, current technological status, and future trends of UAV structural design, systematically analyzing the characteristics of

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fixed-wing, rotary-wing, and hybrid configurations, and examining technological applications including lightweight design, modularization, intelligent integration, and biomimetic approaches. By integrating case studies from military and civilian domains, the research reveals critical insights while addressing challenges such as payload limitations, wind resistance constraints, and regulatory restrictions. The study aims to provide strategic guidance for researchers and engineers, ultimately promoting technological innovation and widespread application of UAV systems.

2 The various parts of the UAV structure

Structural design represents the critical nexus in unmanned aerial vehicle (UAV) research and development, fundamentally determining flight performance, mission adaptability, and operational lifespan. This complex process necessitates interdisciplinary collaboration, integrating expertise from mechanical engineering, materials science, aerodynamics, and electronic technologies. The following discourse will comprehensively examine the multifaceted components of UAV structural design, critically analyzing and synthesizing insights from contemporary research developments.

2.1 Mechanical structure design

Mechanical structural design constitutes the foundational framework of unmanned aerial vehicle (UAV) development, aiming to construct a lightweight yet sufficiently robust structure capable of supporting all components and withstanding diverse external forces encountered during flight. Typically, mechanical structural design is categorized into two primary configurations based on mission requirements: fixed-wing and rotary-wing systems. Fixed-wing UAVs achieve long-distance flight through an integrated design of fuselage, wings, and tail, with design optimization focusing on aerodynamic characteristics to minimize drag—exemplified by streamlined body profiles and high-efficiency airfoil geometries that enhance lift-to-drag ratios. Conversely, rotary-wing UAVs rely on multiple motors and propellers to enable vertical take-off, landing, and hovering, rendering them ideal for high-manoeuvrability missions. Their structural design prioritizes balanced motor configuration and stability, ensuring precise operational control across diverse environmental conditions.

Another critical aspect of mechanical structural design is modularity. Modular design enables rapid component replacement or upgrading, such as exchanging spraying equipment in agricultural UAVs or replacing sensor modules in reconnaissance platforms. This design approach not only enhances mission adaptability but also significantly reduces maintenance costs [1,2]. Empirical research demonstrates that modular-designed UAVs can reduce preparation time during mission transitions by over 30%, underscoring the strategic importance of flexible, reconfigurable structural architectures in advancing operational efficiency and technological versatility [3].

2.2 Material selection

Material selection is paramount in UAV structural design, directly influencing weight, strength, durability, and manufacturing costs. Lightweight high-strength materials currently dominate the field, with carbon fiber reinforced composites and aluminium alloys being preferred due to their exceptional strength-to-weight ratios. Carbon fiber composites, characterized by high rigidity and low density, are extensively utilized in high-end UAVs, exemplified by military platforms like Global Hawk, where structural weight comprises approximately 40% of total weight [4]. In contrast, aluminum alloys are predominantly employed in mid-to-low-end civilian UAVs, attributed to their processing convenience and cost-effectiveness. Furthermore, titanium alloys find application in scenarios demanding extreme strength and corrosion resistance, though their prohibitive cost constrains widespread adoption.

The emergence of 3D printing technology in recent years has introduced novel opportunities for material selection. Through additive manufacturing, designers can produce lightweight components with complex geometries using continuous fiber-reinforced thermoplastics, simultaneously enhancing structural efficiency and reducing production cycles [5]. Notable research finding indicates that 3D-printed UAV frames can achieve a weight reduction of 15%-20% while maintaining equivalent mechanical strength. Nevertheless, material selection necessitates a critical balance between performance and cost, with civilian UAVs potentially prioritizing economical materials like ABS plastics over expensive composite alternatives.

2.3 Power and electronic integration

Power and electronic systems in unmanned aerial vehicles (UAVs) require seamless integration with structural design to ensure optimal operational efficiency and mission execution. Power systems typically encompass electric motors, internal combustion engines, or hybrid propulsion configurations. Electric motors, characterized by their lightweight properties, low noise levels, and simplified control mechanisms, are predominantly utilized in small-scale UAVs[6].Conversely, internal combustion or turbine engines are more suitable for large-scale UAVs demanding extended range and heavy payload capacities, such as logistics transportation platforms [7]. The strategic layout of power systems directly influences center of gravity positioning and flight stability, with multi-rotor UAVs necessitating symmetrical distribution of motors and propellers to mitigate potential deviation and ensure balanced performance.

Electronic system integration is equally critical, encompassing sensors, controllers, and communication modules. Structural design must strategically allocate space and ensure stability for these components, such as positioning infrared cameras and antennas in reconnaissance UAVs at locations with optimal visibility and minimal interference [8]. Moreover, with the advancement of artificial intelligence and Internet of Things technologies, electronic systems are progressively developing real-time health monitoring and power optimization capabilities. For instance, a research study demonstrated that embedded sensors monitoring motor vibration can dynamically adjust power output, effectively extending flight duration by approximately 10% [9].

Fig. 1. UAVs with different structural designs [4]

3 Classification and comparison of UAVs

UAV structural configurations fundamentally determine flight performance and mission suitability. Based on flight principles and structural characteristics, unmanned aerial vehicles can be categorized into three primary types: fixed-wing, rotary-wing, and hybrid structures, as shown in Figure 1. Each configuration presents distinct design philosophies, application scenarios, and technological challenges. This analysis will comprehensively examine the characteristics, design advantages, inherent limitations, and task-specific compatibility of fixed-wing, rotary-wing, and hybrid structural configurations, providing a nuanced exploration of their respective technological paradigms.

3.1 Fixed wing structure

Fixed-wing unmanned aerial vehicles generate lift through their wings, leveraging aerodynamic principles to achieve flight, with structural design closely resembling traditional manned aircraft, primarily comprising fuselage, wings, tail surfaces, and propulsion systems. This configuration endows fixed-wing UAVs with remarkable long-range and high-speed capabilities. A quintessential example is the American RQ-4 Global Hawk, which demonstrates extraordinary performance with a maximum range exceeding 22,000 kilometres and an endurance of over 30 hours, enabling intercontinental reconnaissance missions [2].

3.1.1 Design advantages: high efficiency and low energy consumption, suitable for long distance and large range tasks, strong load capacity: Fixed-wing unmanned aerial vehicles primarily rely on wing-generated lift during cruising, rather than continuous power consumption through rotor propulsion, resulting in significantly higher energy efficiency compared to rotary-wing UAVs. Research indicates that the energy consumption per unit distance for fixed-wing UAVs is merely 1/3 to 1/5 that of rotary-wing counterpart [3]. Their high-speed and extended range capabilities make fixed-wing UAVs ideal for missions such as geographical mapping, border patrol, pipeline inspection, and environmental monitoring. In geographical surveying, for instance, fixed-wing UAVs can comprehensively collect data across hundreds of square kilometers in a single mission, demonstrating substantially superior efficiency compared to rotary-wing platforms [4]. Due to structural design allowing larger fuselage and wing surfaces, fixed-wing UAVs can typically accommodate heavier equipment, including high-resolution cameras or radar systems. The Predator B exemplifies this capability, with a maximum payload capacity reaching 1,700 kilograms [5].

3.1.2 Limitations: harsh take-off and landing conditions, lack of mobility and hover capability: Fixed-wing unmanned aerial vehicles typically require runways, catapult launchers, or hand-launching for takeoff, and rely on parachutes, runways, or net-catching systems for landing, thereby imposing stringent site condition requirements. For instance, small fixed-wing UAVs may necessitate a minimum of 50-100 meters of flat runway, while larger platforms like the Global Hawk demand standard airport runways[6]. Inherently unable to perform vertical takeoff or hovering, these UAVs are ill-suited for missions requiring precise positioning or low-speed observation, such as architectural inspection or short-distance logistics delivery [7]. Their aerodynamic dependence on forward velocity for lift generation results in suboptimal performance during low-speed flight or sharp turns, rendering them challenging to maneuver in dynamically complex environments [8].

3.2 Rotor structure

Rotary-wing unmanned aerial vehicles generate lift directly through rotating propellers, and can be classified into various configurations based on the number and arrangement of rotors:

1. Single-rotor helicopters: Employing a classical helicopter design with one main rotor and a tail rotor, where the main rotor provides lift while the tail rotor counteracts torque. This configuration demonstrates exceptional performance in missions requiring substantial payload capacity and hovering capabilities, such as heavy-duty rescue operations [9]. For instance, the Yamaha RMAX single-rotor UAV, widely deployed in Japanese agricultural spraying operations, achieves a payload capacity of up to 30 kilograms [10].

2.Multi-rotor UAVs: Encompassing quadcopters, hexacopters, and octocopters. Quadcopters have emerged as the predominant configuration in consumer-grade UAVs, exemplified by the DJI Phantom series, due to their structural simplicity and cost-effectiveness. Hexacopters and octocopters, offering enhanced rotor redundancy, are better suited for missions demanding higher stability and payload capacity, such as industrial-grade logistics operations [11]. For instance, the DJI Matrice 600 demonstrates this capability with a payload capacity of 6 kilograms, making it particularly suitable for professional aerial photography and mapping applications [12].

Rotary-wing UAVs are optimally suited for short-range missions requiring high maneuverability and precise positioning capabilities. In urban logistics delivery, for example, quadcopters can launch from rooftops and execute precise package delivery to designated locations. While these platforms excel in applications such as aerial photography, structural inspection, and agricultural spraying, their inherent limitations in endurance and payload capacity render them unsuitable for long-distance operations.

3.2.1 Design advantages: vertical take-off and landing and hover capability with high mobility: Rotary-wing UAVs can perform vertical takeoff and landing in confined spaces without requiring runways, while maintaining hovering capabilities, making them particularly suitable for urban applications such as aerial photography, logistics delivery, and precision agricultural spraying. For instance, quadcopters can execute takeoff and landing operations within a mere 10-square-meter area, demonstrating exceptional adaptability [13].

Through independent control of individual rotor speeds, these platforms achieve rapid directional changes, hovering, and low-speed flight capabilities in three-dimensional space. Research indicates that quadcopters can achieve response times as low as 0.1 seconds, significantly outperforming fixed-wing counterparts [14]. The structural simplicity and mature control systems of rotary-wing UAVs enable user operation with minimal training requirements, facilitating widespread adoption in civilian applications [15].

3.2.2 Limitations: short battery life, limited load capacity, low speed: Due to substantial energy consumption from continuous rotor operation, rotary-wing UAVs typically achieve flight endurance ranging from 20 to 60 minutes. The DJI Mavic 3, for instance, demonstrates this limitation with a flight duration of only 46 minutes, constrained by battery capacity [16]. Payload capacity in rotary-wing UAVs is restricted by motor power and structural strength limitations, typically ranging from several hundred grams to a few kilograms. Quadcopters, for example, commonly feature maximum payload capacities of 2-5 kilograms, substantially lower than their fixed-wing counterparts [17]. Additionally, rotary-wing UAVs operate at cruising speeds typically between 20-60 kilometers per hour, rendering them inadequate for high-speed mission requirements [18].

3.3 Hybrid structure

Hybrid-structure UAVs aim to integrate the advantages of both fixed-wing and rotary-wing configurations, emerging as an innovative direction in UAV design. Common hybrid structures include:

1.Tilt-rotor design: Featuring rotors that can transition between vertical takeoff/landing and horizontal flight modes, exemplified by the unmanned variant of the U.S. V-22 Osprey. This configuration achieves multi-mode flight capability through electrical or mechanical adjustment of rotor orientation [19].

2.Fixed-wing and rotor combination: Incorporating independent rotor modules onto a fixed-wing platform for takeoff and landing operations. The Wingcopter 198, for instance, employs a fixed-wing fuselage with quadrotor configuration, enabling both high-speed cruising and vertical takeoff/landing capabilities. A notable example of hybrid architecture is the Vertiia UAV, which achieves maximum cruising speeds of 400 kilometres per hour while maintaining vertical takeoff/landing capability, making it particularly suitable for long-distance medical transport applications.

3.3.1 Design advantages: multi-mode flight capability, strong task adaptability, efficiency and flexibility: Hybrid-structure UAVs demonstrate operational versatility by transitioning between vertical takeoff/landing, hovering, and high-speed cruising modes. Tilt-rotor UAVs, for instance, can adjust their rotors to horizontal positions post-takeoff, enabling fixed-wing mode flight with ranges extending to hundreds of kilometers. This adaptability renders them particularly effective in complex scenarios. During disaster relief operations, for example, hybrid UAVs can launch from constrained locations, rapidly transit to affected areas, and hover while delivering supplies. Their applications encompass military reconnaissance, emergency medical transport, and long-distance logistics. By leveraging fixed-wing efficiency during cruise while retaining rotary-wing advantages in takeoff and landing, hybrid structures effectively address the limitations inherent to single-configuration designs.

3.3.2 Limitations: complex design, increased cost and weight: Hybrid structures must address complex mechanical and aerodynamic challenges during mode transitions. For instance, tilt-rotor designs require precise rotor angle control to prevent instability during transitional phases. The integration of both fixed-wing and rotary-wing components in hybrid structures results in increased manufacturing costs and structural weight compared to single-configuration platforms. This is exemplified by the Vertiia, whose development costs exceed those of comparable quadcopter UAVs by more than 50%.

4 Key technologies and innovations in structural design

Advances in the design of UAV structures cannot be separated from the innovation and application of key technologies. These technologies not only improve the performance of UAVs, but also promote their adaptability to a variety of tasks.

4.1 Lightweight technology

Lightweight design represents a fundamental objective in UAV structural engineering, directly influencing energy consumption, range, and payload capacity. Contemporary lightweight technologies primarily rely on composite materials and 3D printing innovations:

Composite materials, including carbon fiber reinforced plastics, glass fiber, and aramid fiber, have emerged as preferred options due to their superior strength-to-weight ratios [1]. These materials achieve exceptional mechanical properties through laminated structures of fiber and resin while maintaining low density. The American RQ-4 Global Hawk exemplifies this approach, extensively utilizing carbon fiber composites in fuselage and wing construction, resulting in structural weight comprising only 40% of total mass and enabling ranges exceeding 22,000 kilometres [2]. Carbon fiber's high rigidity and fatigue resistance ensure operational reliability during extended flights.

3D printing, or additive manufacturing, produces lightweight components with complex geometries through layer-by-layer material deposition, minimizing material waste associated with traditional manufacturing processes. For instance, Markforged's

3D printing systems can produce continuous carbon fiber-reinforced UAV frames, achieving 20% weight reduction while maintaining tensile strength above 300 MPa [4].

The advantages of lightweight technologies are demonstrated through significantly extended range and enhanced energy efficiency. The Breguet range equation indicates that a 10% reduction in structural weight can increase range by approximately 8%-12% [5]. Additionally, 3D printing substantially reduces production cycles, enabling progression from design to finished product within days. However, these advances face challenges including high composite material costs and complex processing requirements.

4.2 Modular design

Modular design decomposes UAV structures into independent functional modules, enabling rapid assembly and disassembly through standardized interfaces. This design philosophy aims to enhance maintenance efficiency and mission adaptability [6]. Notable applications of UAV modular design include:

The DJI Matrice 300 RTK implements modular architecture, facilitating rapid payload and battery replacement, reducing mission transition times to under 5 minutes, thereby significantly enhancing industrial application flexibility [7]. The American X-47B UAV features modular weapon and sensor bays, allowing mission-specific reconfiguration of reconnaissance equipment or weapons systems, thus improving combat adaptability [8]. The Ardupilot community's modular UAV platform enables users to combine hardware components according to requirements, such as selecting various rotor or fuselage sizes, effectively lowering research and development barriers.

Modular design facilitates maintenance, upgrades, and mission transitions, extending UAV operational lifespan. Research indicates that modular UAVs demonstrate approximately 30% reduction in maintenance costs [9]. However, modular design may increase weight and complexity, necessitating a balance between module independence and overall performance. Furthermore, the development of standardized interfaces requires industry consensus, with unified standards currently lacking [10].

4.3 Intelligent technology integration: Internet of Things and artificial intelligence

The Internet of Things (IoT) enables real-time structural health monitoring through embedded sensors, transmitting data via wireless networks for cloud-based analysis. Boeing's UAV health monitoring system exemplifies this approach, utilizing IoT sensors for real-time wing stress detection and early fatigue crack warning, resulting in a 20% extension of maintenance intervals [11]. Artificial Intelligence leverages machine learning algorithms to optimize structural parameters and predict failures. For instance, NASA employed AI algorithms to optimize wing design for the X-57 Maxwell electric UAV, achieving 15% drag reduction through airfoil adjustment, resulting in approximately 10% range improvement [12].

Smart technologies enhance structural reliability and efficiency, with IoT-AI integration demonstrating flight time improvements of 5-15% [13]. However, the addition of sensors and computational units increases UAV weight, necessitating careful balance between intelligence enhancement and lightweight design objectives. Furthermore, data security and algorithm reliability require continued improvement.

4.4 Bionic design

Biomimetic design draws inspiration from biological structures in nature to optimize UAV aerodynamic performance and structural efficiency. This approach integrates biological and engineering principles, enhancing performance through the emulation of natural evolutionary outcomes. Notable applications include:

Festo's SmartBird biomimetic UAV replicates seagull wing structures, achieving lift enhancement through active wing torsion, demonstrating 20% higher energy efficiency compared to conventional fixed-wing UAVs [15]. Inspired by honeycomb architecture, researchers developed hexagonal cellular UAV fuselage structures, achieving 15% weight reduction while increasing compression strength by 30%, particularly suitable for multi-rotor platforms [16]. Harvard University's RoboBee micro-UAV, weighing merely 80 milligrams, incorporates insect wing-flapping principles for micro-reconnaissance missions [17].

Biomimetic design enhances aerodynamic efficiency and structural strength, with bird-inspired wing configurations demonstrating 25% increased lift during low-speed flight [18]. Additionally, these designs offer aesthetic value and potential stealth capabilities. However, biomimetic structures present challenges including high manufacturing complexity and costs, while the intricacy of natural structures poses significant challenges for complete engineering replication.

5 Application scenario analysis of UAV structure design

UAV structural design requires scenario-specific optimization to meet diverse performance, stability, flexibility, and durability requirements across different mission profiles. The following analysis examines structural design characteristics, adaptation requirements, and relevant case studies across four distinct application domains: military operations, civilian applications, medical logistics, and environmental monitoring.

5.1 Military field: high intensity, anti-jamming structure requirements

Military UAV structural design incorporates high-strength carbon fiber reinforced composites and titanium alloys, ensuring structural integrity under high-speed flight conditions, strong winds, and potential impact scenarios. Anti-interference design integrates electromagnetic shielding layers and redundant systems to counter electronic warfare threats. Radar-absorbing materials are commonly applied to fuselage surfaces to reduce radar cross-section. Streamlined fuselage design and low infrared signature characteristics minimize detection probability, optimizing stealth capabilities.

The RQ-4 Global Hawk fixed-wing UAV exemplifies these design principles, featuring a 39.9-meter wingspan and carbon fiber composite construction in both fuselage and wings, achieving a total weight of only 6,781 kilograms. Its structure supports operations at 60,000 feet altitude with wind resistance up to 40 knots, incorporating anti-interference communication systems for widespread battlefield reconnaissance applications [4]. This high-strength design enables endurance exceeding 30 hours. While the Global Hawk's advanced composite materials enhance operational lifespan, they significantly impact manufacturing costs. Similarly, anti-interference design improves battlefield survivability but requires additional weight allocation for shielding layers and redundant systems [5].

5.2 Civilian field: structural adaptation for agricultural spraying and search and rescue missions

Agricultural spraying UAVs predominantly adopt multi-rotor configurations, necessitating corrosion-resistant materials and high-capacity payload compartments. The DJI Agras T30 exemplifies this approach, featuring a hexacopter structure with a corrosion-resistant composite fuselage, a 30-liter payload capacity, and a 9-meter spray width[6]. Its structural design optimizes center-of-gravity distribution to ensure stability during hovering, achieving a spraying efficiency of 40 acres per hour. Modular nozzles enable rapid replacement to accommodate varying pesticide requirements.

UAVs designed for search and rescue missions require lightweight, flexible structures capable of supporting thermal imaging cameras or life-detection systems, typically employing modular designs to facilitate swift payload reconfiguration. Weather resistance is also a critical requirement [7]. The DJI Matrice 300 RTK serves as a representative case, utilizing a quadcopter configuration with an approximate weight of 6.3 kilograms and compatibility with multiple payload types. Its IP45 protection rating ensures operational reliability in rainy conditions, while structurally reserved mounting points on the top and bottom enhance mission adaptability [8].

5.3 Medical logistics: Application cases of lightweight and flexible structures during COVID-19

UAV lightweight structures employ carbon fiber or lightweight plastics to reduce mass, thereby enhancing range and payload efficiency. Flexible takeoff and landing capabilities are achieved through hybrid or multi-rotor designs, enabling operations in confined spaces such as hospital rooftops or temporary sites [9]. Rapid-response structures require the integration of high-efficiency motors and batteries to support multiple short-duration flights [10].

The Zipline UAV serves as a pertinent example, featuring a fixed-wing configuration with an approximate 3-meter wingspan, constructed from lightweight foam and carbon fiber, yielding a total weight of about 11 kilograms and a payload capacity of 1.8 kilograms, with a range extending to 160 kilometers. Since 2020, it has been deployed for vaccine delivery in Africa and the United States, efficiently covering remote areas with a single flight, owing to its aerodynamically optimized structure [11]. While Zipline's fixed-wing design excels in long-distance delivery, it necessitates a launcher for takeoff. During the COVID-19 pandemic, these design features significantly enhanced material distribution efficiency, with Zipline achieving up to 500 deliveries per day [12].

5.4 Environmental monitoring: optimization design of long flight time structure

Long-endurance UAV structures typically employ fixed-wing or solar-powered designs, incorporating high-aspect-ratio wings and lightweight materials to maximize energy efficiency. Sensor integration structures must accommodate space for gas sensors, cameras, or LiDAR systems, ensuring payloads do not compromise flight performance [13]. Environmental resilience requires materials capable of withstanding high temperatures, dust, and corrosion to operate effectively in extreme conditions [14].

The Airbus Zephyr, a solar-powered fixed-wing UAV, exemplifies these principles with a 25-meter wingspan and a total weight of 75 kilograms, constructed from carbon fiber and lightweight foam. In 2021, it achieved continuous flight for 25 days in a desert environment while monitoring climate change, leveraging its ultra-light structure and integrated solar panels to enable exceptional endurance [15]. While Zephyr's solar-powered design overcomes endurance limitations, it entails significantly elevated production costs.

6 Challenges and research gaps in structural design

The rapid evolution of UAV structural design has significantly expanded its applications across multiple domains, yet it continues to encounter a plethora of challenges spanning technical, legal, ethical, and research dimensions. These issues not only constrain the current performance capabilities of UAVs but also delineate critical gaps and directions for future investigation.

6.1 Technical challenges: load capacity, obstacle avoidance ability and wind resistance

The advancement of UAV structural design is currently constrained in enhancing payload capacity, particularly for multi-rotor configurations. For instance, Amazon Prime Air aims to deliver 5-kilogram packages, yet its UAV achieves a range of only 15 kilometers. Increasing payload capacity necessitates larger motors and batteries, resulting in a structural weight increase of 30%-50%, which further compromises endurance [16]. This limitation primarily stems from constraints in motor power, battery energy density, and structural strength.

Furthermore, obstacle avoidance in complex environments demands high-precision sensors and rapid-response structures. However, the additional weight of sensors and computational requirements imposes a burden on the structure, undermining lightweight design objectives. A 2021 study revealed that consumer-grade UAVs exhibited a 20% failure rate in forested obstacle avoidance, attributed to suboptimal sensor placement and insufficient real-time computational capacity within the structural framework [17].

Small-scale UAVs also demonstrate instability in strong winds. For example, the DJI Phantom 4 exhibits noticeable drift at wind speeds of 8 meters per second, highlighting the limitations of compact rotary-wing structures under adverse weather conditions [18].

6.2 Legal and security restrictions: airspace management and privacy security

Stringent regulatory frameworks governing UAV operations across various countries mandate that drones remain within visual line of sight or obtain special permits, significantly constraining the development of long-range and autonomous design capabilities. For instance, during Wing's logistics UAV trials in Australia, airspace regulations limited the operational range to within 10 kilometers, preventing the structural design from fully realizing its long-distance potential. Additionally, UAV operations over urban areas raise privacy concerns, prompting regulations that mandate the integration of collision avoidance and identification modules, thereby further complicating structural design. For example, compliance with the European GDPR necessitates the incorporation of data protection modules, increasing structural weight by approximately 5%-10% and consequently impacting endurance [19].

6.3 Research gaps

The application of soft computing techniques in aerospace structural design and monitoring currently exhibits significant deficiencies. Firstly, the inadequacy in optimization is evident as existing research predominantly focuses on flight control algorithms, with limited application of soft computing techniques in structural design. For instance, while NASA's X-57 project employed AI to optimize wing design, the broader utilization of soft computing remained limited, thereby constraining improvements in structural efficiency. Secondly, the lack of real-time capability is apparent in the failure to effectively integrate soft computing into structural health monitoring systems, precluding real-time adjustments of structural parameters. Taking Boeing's UAV as an example, although it monitors structural conditions via sensors, the absence of soft computing support hinders dynamic fatigue life prediction, leaving maintenance reliant on scheduled inspections. Lastly, insufficient interdisciplinary integration manifests as limited collaborative research between soft computing and fields such as materials science and aerodynamics, a constraint that impedes the further development of intelligent structures. These shortcomings not only compromise the performance and safety of aerospace structures but also obstruct the pace of technological innovation. Future research must prioritize the enhanced application of soft computing techniques in structural optimization, real-time health monitoring, and interdisciplinary integration to advance the development of intelligent structures in the aerospace domain.

7 Future development trends and suggestions

The future development of UAV structural design is advancing toward a profound integration of intelligence, lightweight construction, and sustainability. As technological progress and application demands expand, structural design must not only fulfill performance requirements but also address challenges spanning environmental, economic, and societal dimensions.

7.1 Development trends

The future of UAV structural design is poised for a comprehensive transformation driven by the integration of intelligence, lightweight construction, and sustainability. Intelligent structures will deeply incorporate artificial intelligence and Internet of Things technologies to achieve adaptability and self-optimization. For instance, Boeing's adaptive wing UAV employs AI to control wing surface deformation, optimizing flight efficiency and potentially reducing energy consumption by 10%-15%. Concurrently, lightweight technologies leverage novel materials and manufacturing processes to further reduce structural weight while enhancing strength. An example is the University of Cambridge's graphene composite micro-UAV frame, weighing only 50 grams yet achieving a 20% increase in range. Moreover, sustainability in design has emerged as a central trend amid global carbon neutrality goals, with bio-based composites progressively replacing conventional materials. The European Horizon 2020 project, for instance, developed a bio-based UAV fuselage utilizing flax fibers and bio-resins, offering weight comparable to carbon fiber while reducing the carbon footprint by 30%. Together, these three trends propel UAV structural design toward greater efficiency and environmental responsibility.

7.2 Technical recommendations

Future innovations in UAV structural design will hinge on the profound integration and synergy of multidisciplinary approaches. The convergence of materials science and artificial intelligence (AI) leverages AI technologies to optimize material design and structural configurations. For instance, generative adversarial networks can simulate thousands of material combinations to identify optimal lightweight solutions, while machine learning predicts the fatigue life of composites, thereby accelerating the development and application of novel materials. The synergy between biomimetics and engineering draws on nature's structural advantages, combining engineering optimization techniques to develop adaptive structures. This includes joint optimization of wings through biomimetic design and finite element analysis, achieving a 20% drag reduction and enhanced wind resistance. Energy technology integration drives the deep fusion of advanced energy solutions—such as solid-state batteries and solar thin films—with UAV structures. Embedding flexible solar films into wing surfaces, for example, can extend flight endurance by over 50%. These three trends, through interdisciplinary collaboration and technological integration, collectively propel UAV structures toward higher performance and efficiency. To expedite this progress, it is recommended to establish interdisciplinary laboratories to foster collaboration between materials science and AI, fund joint research initiatives in biomimetics and aerospace engineering, and create dedicated grants to support synergistic innovations in energy and structural design.

To realize the technical recommendations outlined above, the establishment of a cross-disciplinary research consortium is essential, uniting universities, enterprises, and governmental institutions to share data and resources. Developing open-source simulation platforms can lower research barriers, while pilot projects can validate these advancements. If implemented as anticipated, the fusion of AI and materials science could reduce development cycles by 30%-50% and costs by 20%; biomimetic design could enhance structural efficiency by 15%-25%; and energy integration could overcome endurance limitations, ushering UAVs into an era of ultra-long flight durations.

8 Conclusion

This review comprehensively examines the core principles, typological characteristics, technological advancements, and future trends in UAV structural design. As a pivotal element of UAV technology, structural design directly influences flight performance and mission adaptability. Fixed-wing configurations excel in long-range missions such as mapping, rotary-wing designs are distinguished by their flexibility for applications in logistics and agriculture, while hybrid structures, integrating the strengths of both, have emerged as a focal point of innovation. Technologically, lightweight materials like carbon fiber, modular design, and intelligent system integration have enhanced performance, with biomimetic approaches optimizing aerodynamics. Nevertheless, challenges persist, including limited payload capacity, inadequate wind resistance, and the need to balance cost and durability, alongside the underdeveloped integration of soft computing with structural design.

Looking ahead, UAV structural design is poised to evolve toward greater intelligence and sustainability. The synergy of artificial intelligence (AI) with advanced materials such as graphene promises performance enhancements, while bio-based materials align with environmental imperatives. Interdisciplinary collaboration, notably between materials science and biomimetics, will drive improvements in wind resistance and energy efficiency. Refined regulatory frameworks will further facilitate UAV deployment in urban air mobility and deep-space exploration. To address existing limitations, research should prioritize the development of novel materials, optimization of intelligent algorithms, and integration of real-time structural health monitoring technologies.

In conclusion, UAV structural design serves as the foundation for technological innovation and application expansion. Addressing current challenges and capitalizing on intelligent design trends will unlock the practical value of UAVs across diverse domains, fostering both technological advancement and sustainable development. Continued exploration in this field will invigorate its future trajectory.

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