Study on Landing Gear Stability in Quadrotor UAVs

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Abstract. This paper focuses on the stability of landing gear systems for quadrotor UAVs. As drones are increasingly deployed across diverse applications including precision agriculture, emergency logistics, and infrastructure inspection, landing gear stability becomes critical to ensuring safe and reliable operation especially during repeated takeoff and landing cycles. The study aims to dissect factors influencing quadrotor UAV landing gear stability and propose optimized design methodologies and enhancement strategies. Internationally, significant advancements have been achieved in structural design, material innovation, and shock absorption technologies for landing gear; however, challenges persist in adapting to extreme environments and balancing miniaturization with high performance. Domestic research has also progressed, yet gaps remain in interdisciplinary integration and studies under extreme operational conditions such as asymmetric impact loads. The paper provides a detailed analysis of structural characteristics, advantages, and limitations of fixed-type, wheel-type, and foldable landing gear configurations, offering tailored recommendations and solutions to address their respective shortcomings.

Keywords: Landing Gear Stability, Stability Analysis, Landing Gear Design, Impact Absorption

1 Introduction

1.1 Research Background and Significance

With the rapid advancement of technology, unmanned aerial vehicles (UAVs) have evolved into indispensable tools in modern society, demonstrating vast application potential across military reconnaissance, geographic mapping, agricultural crop protection, logistics delivery, cinematography, and environmental monitoring. UAVs transcend geographical and human labor constraints, efficiently executing complex tasks while significantly enhancing operational efficiency and quality.

Throughout a UAV's flight cycle, landing gear stability plays a pivotal role. During takeoff, stable landing gear ensures smooth ground departure, mitigating risks of flight deviations or loss of control caused by initial instability. The landing phase poses an even greater challenge to stability—whether on paved runways or rugged terrain, landing gear must effectively absorb landing impact forces, maintain equilibrium, and prevent tilting, overturning, or damage to sensitive onboard instrumentation due to

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excessive vibrations. Stable landing gear is foundational to ensuring mission safety, precision, and the broader adoption of UAVs, underscoring its critical importance for reliable operations.

1.2 Research Objectives

This study focuses on the stability of quadrotor UAV landing gear systems, with the primary objective of thoroughly investigating the multifaceted factors influencing their stability. By synthesizing and summarizing existing research, the study identifies common challenges and proposes practical, actionable design optimizations—including structural modifications, material innovations, and other critical aspects—while formulating effective enhancement strategies. These efforts aim to comprehensively improve the stability of quadrotor UAV landing gear, enhance the adaptability of UAVs to complex environments and operational conditions, and thereby provide robust support for the safe and efficient advancement of UAV technology.

1.3 Current Research Landscape: Domestic and International

Abroad, remarkable achievements have been made in the field of landing gear structural design, with diverse structural forms developed for different scenarios, demonstrating excellent applications in both military and civilian drones, such as retractable and foldable landing gears for easy installation. High-performance materials like carbon fiber composites and titanium alloys have been actively adopted to enhance performance, alongside significant advancements in cushioning and shock absorption technologies, such as advanced hydraulic buffer systems integrated with smart sensors to ensure smooth landings. However, there remains room for optimization in adaptability to extreme and complex environments, as well as challenges in balancing miniaturization with high performance.

In China, research on landing gear stability has achieved certain results. Universities and research institutions actively participate, conducting in-depth explorations through theoretical analysis combined with experiments. Theoretically, continuous improvements have been made to mechanical models, employing methods like finite element analysis to optimize landing gear structural design and enhance strength and stability. For instance, some studies construct models based on different material properties to guide material selection for landing gears, improving their fatigue and impact resistance. Experimentally, diverse testing platforms have been established to simulate various working conditions, such as takeoff and landing processes under different terrains and wind speeds, enabling precise measurement of landing gear stress and deformation data to effectively validate and refine theoretical outcomes. Meanwhile, some enterprises prioritize landing gear stability improvements in UAV product development, adopting innovative designs like specialized shock-absorbing structures and adaptive adjustment mechanisms to enhance takeoff and landing adaptability in complex environments. Nevertheless, domestic research still faces shortcomings. There is insufficient depth in interdisciplinary integration—for example, studies that tightly integrate materials science, control technology, and mechanical principles to achieve comprehensive performance optimization of landing gears remain underdeveloped. Research on landing gear stability in extreme and complex environments, such as high-altitude regions and scenarios with strong electromagnetic interference, lacks comprehensiveness and depth, necessitating further increases in R&D investment and innovation efforts to narrow the gap with international advanced standards.

2 Analysis of Typical UAV Landing Gear Structures

2.1 Fixed Landing Gear

The fixed landing gear is a common structural configuration, consisting of two parallel, fixed rods (see Figure 1). It features a simple structure, lightweight design, low cost, and easy installation. During takeoff and landing, the rods contact the ground to provide support and cushioning [1]. However, the cushioning performance of fixed landing gear is relatively poor, and its limited pressure-bearing capacity during landing can lead to unstable touchdowns under high-speed descents. Additionally, fixed landing gear requires high ground flatness; operations on uneven terrain increase the risk of tipping. Therefore, during design, it is critical to ensure stable landings under diverse conditions, such as high-speed vertical descents or rapid taxiing, to guarantee safety [2]. While prioritizing landing safety, material selection should emphasize lightweight and durable options while maintaining cost-effectiveness to maximize economic value.

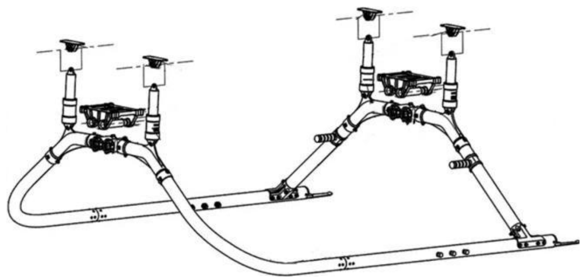

Fig. 1. Fixed Landing Gear

2.2 Wheeled Landing Gear

The structural composition of wheeled landing gear is relatively complex, with varying characteristics across different layout configurations. Taking the four-point wheeled landing gear as an example, it consists of a landing gear frame, connection mechanisms, and an equipment bay. The frame is further divided into a front-wheel frame and a rear-wheel frame. The front-wheel frame shown in Figure 2 includes components such as the front wheel, front-wheel bracket, and front-wheel axle, while the rear-wheel frame follows a similar structure [3]. This intricate design endows wheeled landing gear with unique performance characteristics in practical applications. From an advantage perspective, wheeled landing gear plays a critical role during ground operations and takeoff phases of UAVs. It provides the necessary acceleration for takeoff, ensuring smooth ascent. During ground taxiing, takeoff, and landing, the wheeled system offers stable support, maintaining attitude stability and reducing risks caused by uneven ground contact [4]. However, it is important to note that wheeled landing gear also has limitations. The complex structure increases weight, which inevitably impacts UAV flight efficiency. Additionally, the heightened structural complexity elevates manufacturing costs, including raw material procurement and processing expenses. Given these characteristics, the design of wheeled landing gear requires a comprehensive balance of multiple factors. Material selection is paramount: lightweight materials should be prioritized to reduce overall weight and enhance flight performance while ensuring strength and stability [5]. Concurrently, cost control must be emphasized through optimized manufacturing processes and material choices to maximize economic efficiency without compromising design requirements.

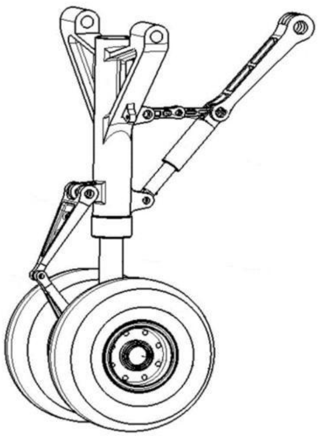

Fig. 2. Wheeled Landing Gear

2.3 Foldable Landing Gear

Foldable landing gear typically relies on specialized hinges, pivots, or other movable linkage components to achieve folding functionality (see Figure 3), offering significant advantages in optimizing UAV space utilization [6]. When the UAV is non-operational, foldable landing gear substantially reduces the overall volume of the drone, greatly facilitating storage, portability, and transportation, thereby enhancing mobility and user convenience [2]. Furthermore, its flexible deployment and retraction processes adapt to diverse usage scenarios and storage conditions, broadening the UAV's application scope [7]. However, foldable landing gear also presents challenges. The added folding mechanisms increase structural complexity, elevating design and manufacturing difficulties while potentially adding weight that compromises flight performance. Moreover, under high-impact loads, folding joints may compromise overall structural integrity and stability, posing potential risks to takeoff and landing safety. To address these characteristics, critical design priorities must be emphasized. First, the landing gear must operate stably and precisely during both deployment and folding to prevent functional failures [8]. Material selection must balance strength, weight, and cost, prioritizing high-strength, lightweight materials to reduce UAV weight without sacrificing functionality. Additionally, folding components require specialized reinforcement through optimized geometries and connection methods to enhance strength and stability, ensuring reliable performance across all operational conditions.

Fig. 3. Foldable Landing Gear

3 Discussion and Outlook

The fixed landing gear is the simplest in structure, lowest in cost, and most convenient to install among the three types. However, fixed landing gear underperforms in complex landing environments particularly when encountering uneven surfaces or high-impact landings. It is recommended to use high-strength lightweight materials, such as carbon fiber reinforced polymers which offer exceptional strength-to-weight ratios exceeding traditional aluminum alloys, to enhance its load-bearing capacity. Wheeled landing gear provides stable support, takeoff acceleration, and steering capabilities. However, its complex structuretypically requiring multiple bearing assemblies and steering linkages, higher weight, elevated costs due to precision manufacturing requirements, and limited adaptability to challenging landing conditions remain drawbacks. Structural optimization through finite element analysis and topology optimization algorithms to eliminate redundant components is advised. Foldable landing gear excels in portability and scenario flexibility enabling compact storage for transportation-constrained UAVs. Yet, constrained by its design particularly at hinge and pivot points, foldable landing gear generally exhibits lower material strength and requires durability improvements. Recommendations include combining high-strength engineering plastics like PEEK (polyether ether ketone) with metals through hybrid manufacturing techniques for folding components to enhance joint strength and designing high-precision locking mechanisms with micron-level tolerances to ensure stable deployment/retraction and safe UAV operations.

All three landing gear types share a common limitation: difficulty in ensuring landing safety in complex environments such as mountainous terrain or shipboard operations and under high-load scenarios including heavy payload transport missions. To address this, damping structures—such as spring-based or hydraulic damping systems [9] (see Figure 4)—can be integrated at the connection points between the landing gear and the UAV body using vibration-isolation mounts, as well as at ground contact interfaces through adaptive footpad designs. Additionally, integrating PID control systems [10] (see Figure 5) for intelligent damping adjustment enabling real-time stiffness modulation based on inertial measurement data offers dual benefits: enhancing load-bearing capacity through dynamic force distribution and durability while improving adaptability to complex terrains via terrain recognition algorithms, thereby expanding UAV application scenarios including disaster relief and Arctic exploration. Current research gaps in bionics-inspired damping structures such as insect leg shock absorption mechanisms present opportunities to further advance landing gear stability through biomimetic design innovationslike hierarchical cellular structures mimicking bone trabeculae.

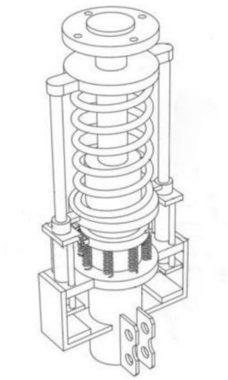

Fig. 4. hydraulic damping systems

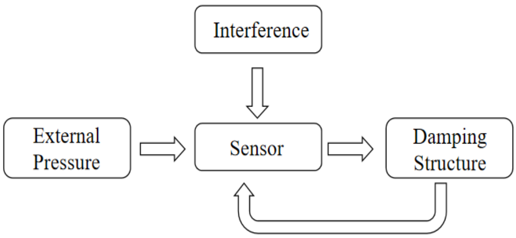

Fig. 5. PID control systems

4 Conclusion

This paper systematically reviews critical issues and research advancements in the stability of landing gear systems for quadrotor UAVs through comprehensive analysis of academic literature and industrial patents. The study highlights that landing gear stability directly impacts UAV safety during takeoff and landing phases especially in scenarios involving abrupt terrain transitions or dynamic payload shifts, particularly emphasizing the importance of shock absorption capabilities and structural reliability in complex environments. The advantages and limitations of fixed, wheeled, and foldable landing gear configurations are analyzed using combined experimental and computational approaches. Comparative analysis of domestic and international research reveals that abroad, significant achievements have been made in structural innovation such as hierarchical lattice architectures and material applications (e.g., carbon fiber, titanium alloys), yet challenges persist in extreme environment adaptability including thermal cycling extremes and balancing miniaturization with operational robustness. Domestic research, while progressing in mechanical modeling and experimental validation leveraging advanced motion capture systems, lacks interdisciplinary integration with fields like soft robotics and requires deeper exploration of stability under extreme conditions characterized by erratic aerodynamic disturbances. To address existing challenges, recommendations include optimizing landing gear performance through lightweight high-strength materials (e.g., carbon fiber, metal-polymer composites), intelligent damping systems (e.g., hydraulic-PID control), and biomimetic design drawing inspiration from arthropod exoskeletons, alongside enhanced extreme-environment simulations employing multiscale modeling frameworks and multidisciplinary collaborative research bridging aerospace engineering and ecological biomechanics. Future efforts should prioritize structural lightweighting through metastructure design, intelligent adaptive adjustment mechanisms utilizing distributed sensor networks, and biomimetic damping technologies emulating natural energy dissipation strategies to comprehensively improve UAV safety and operational versatility in complex scenarios ranging from urban search-rescue to extraterrestrial exploration.

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