

A Review of Research on Multi-Modal UAV Technology: From Structural Innovation to Intelligent Control

Minjun Xu *

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China

* Corresponding Author Email: 824173465@qq.com

ABSTRACT

By integrating multiple modes of locomotion, such as aerial, ground, and surface or underwater operations, multi-modal unmanned aerial vehicles (UAVs) overcome the inherent limitations of single-mode robots in terms of endurance, terrain adaptability, and operational range. They have thus become a significant research direction in the field of robotics. This paper systematically reviews the recent research progress in multi-modal UAV technology, presenting a comprehensive overview from four dimensions: system configuration, key technologies, challenges, and future trends. In terms of configuration, amphibious aerial-ground, aerial-aquatic, and tri-modal UAVs are classified according to their structural design characteristics, and the advantages, disadvantages, and applicable scenarios of solutions such as wheeled, legged, and morphing structures are analyzed. Regarding key technologies, this review summarizes existing research achievements and their limitations, focusing on core issues including motion planning and trajectory optimization, control system design, and cross-medium communication and perception. Building on this analysis, the paper explores the main challenges currently facing multi-modal UAVs, such as structural lightweighting, robustness during mode switching, energy management, and autonomous decision-making. Finally, it identifies the deep integration of structure and function, intelligent control and autonomous decision-making, collaborative swarm operations, and the application of novel energy sources and advanced materials as critical directions for future development.

KEYWORDS

Multi-modal UAV; Amphibious UAV; Structural Design; Motion Planning; Trajectory Tracking Control.

1. INTRODUCTION

With the rapid advancement of robotics technology, unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) have demonstrated extensive application value in fields such as military reconnaissance, disaster relief, environmental monitoring, and logistics distribution. However, single-mode robots suffer from inherent limitations: UAVs are constrained by short endurance and limited payload capacity, while UGVs are significantly restricted by terrain conditions and exhibit limited obstacle-climbing capabilities. To address these shortcomings, multi-modal unmanned aerial vehicles (UAVs) capable of traversing different media have emerged and quickly become a research hotspot in robotics [1].

By integrating multiple locomotion modes, multi-modal UAVs achieve complementary advantages among different forms of movement. For instance, aerial-ground amphibious UAVs combine the high mobility of flight with the long endurance of ground travel [2], while aerial-aquatic amphibious UAVs offer both rapid aerial deployment and covert underwater operation capabilities [3]. Such multi-modal

characteristics enable these vehicles to adapt to complex and changing environments, rendering them significant theoretical research value and promising engineering application prospects.

2. CLASSIFICATION AND DESIGN OF MULTI-MODAL UAV SYSTEM CONFIGURATIONS

The core of multi-modal UAVs lies in the use of innovative mechanical structures to enable locomotion across multiple media. Based on the dimensionality of movement, these vehicles can be primarily categorized into aerial-ground amphibious, aerial-aquatic amphibious, and aerial-ground-aquatic triphibious types. Each configuration has distinct emphases in terms of structural design and functional implementation.

2.1. Aerial-Ground Amphibious UAVs

Aerial-ground amphibious UAVs represent the most extensively studied type, with their structural design primarily focused on the integration of flight systems and ground mobility systems. Among various configurations, the combination of wheels and rotors is relatively common, offering a relatively simple structure and mature control technology. A typical current solution is the ten-degree-of-freedom wheel-legged robot, which combines the efficient mobility of wheels with the obstacle-climbing capability of legged mechanisms [4]. To further enhance ground locomotion efficiency, some studies have adopted morphing structural designs. These employ concealed rotors and gear train transmissions to achieve rotor retraction in ground mode and deployment in flight mode, effectively reducing overall volume and aerodynamic drag [5]. Additionally, foldable arm solutions have been applied for aerial-ground mode transitions, utilizing servo-controlled arm folding and unfolding to achieve rapid switching [6].

Under complex terrain conditions, the combination of legged mechanisms and rotors provides an effective means to enhance adaptability to rugged environments. Current design approaches mainly fall into two categories. The first combines rotors with multi-jointed mechanical legs, utilizing power conversion mechanisms to switch between aerial and ground modes [7]. The second integrates six rotors with six mechanical legs, where the legs are not only used for terrestrial walking but can also perform surface skidding by simulating the butterfly stroke motion, demonstrating multifunctional reuse of structures [8]. In terms of disintegrable designs, combined configurations featuring a quadruped robot and a quadrotor are designed as separable units. These can operate either collaboratively or independently, enhancing the flexibility of system deployment [9]. For such disintegrable structures, a docking mechanism based on a cone-and-rod-like structure enables autonomous docking and separation between the aerial vehicle and the ground robot [10].

2.2. Aerial-Aquatic and Aerial-Ground-Aquatic Triphibious UAVs

Compared to aerial-ground amphibious platforms, aerial-aquatic or triphibious UAVs must simultaneously meet the operational requirements of aerial flight, surface navigation, and underwater traversal across multiple media, imposing higher demands on sealing, anti-corrosion measures, and propulsion systems. In terms of configuration design, the combination of a boat-like fuselage with rotors or thrusters represents a common aerial-aquatic amphibious solution. One study employed a boat-shaped fuselage, where aerial propulsion was provided by rotors and surface navigation was powered by underwater thrusters [11]. Another approach drew inspiration from submarine fuselage design, utilizing tiltable ducted fans and vector nozzles to achieve mode transitions between flight and underwater navigation.

Buoyancy and sealing design are critical for ensuring surface takeoff and landing capabilities as well as flotation stability. Aerial-aquatic amphibious UAVs often employ floats or sealed chambers to provide buoyancy, complemented by reliable waterproof sealing structures to protect internal

electronic components. For instance, the use of polyurethane rubber sealed chambers combined with secondary sealing processes can effectively ensure operational reliability during underwater missions [12].

3. KEY TECHNOLOGY RESEARCH PROGRESS

The realization of multi-modal UAVs relies on efficient motion planning and trajectory optimization, robust control systems, and reliable cross-medium communication and perception capabilities. These technologies are interdependent and collectively determine the autonomy and environmental adaptability of the platform.

3.1. Motion Planning and Trajectory Optimization

Motion planning and trajectory optimization are critical for autonomous operation. For aerial modes, existing research often exploits the differential flatness property of multirotor vehicles to transform complex trajectory planning problems into optimization problems in a low-dimensional flat output space, employing the minimum-snap method to generate smooth and dynamically feasible flight trajectories. Considering the multi-modal and variable operating condition characteristics of aerial-ground amphibious UAVs, some studies have proposed a multi-modal hybrid A* path planning method. This approach constructs an elevation-occupancy hybrid map and incorporates a power consumption-based cost function into the front-end path search, enabling the planned path to automatically select the optimal locomotion mode based on terrain conditions [13].

In path search, the A* algorithm and its variants are commonly used for global path planning for ground mobility, often combined with algorithms such as TEB for local dynamic obstacle avoidance. For instance, integrating an optimized A* algorithm with the TEB algorithm can effectively enable unmanned ground vehicle navigation in dynamic environments [14]. For morphing robots with crawling capabilities, establishing forward and inverse kinematics models of individual legs using analytical methods and analyzing the sequence of crawling actions represents a common current approach [15].

3.2. Control System Design

Control system design is central to achieving stable multi-modal motion. For ground motion control, particularly for wheeled or wheel-legged structures, a common practice involves establishing a ground motion model that includes steering and speed control, and subsequently designing a cascade PID controller to achieve closed-loop control of velocity and heading. For systems with complex dynamic models, super-twisting sliding mode controllers can be combined with LQR controllers to handle steering and motion control respectively. In flight control, mainstream methods include cascade PID, LQR, and Active Disturbance Rejection Control (ADRC). In complex aquatic environments, combining cascade PID with fuzzy adaptive PID can effectively enhance the control accuracy and anti-disturbance capability of aerial-aquatic amphibious UAVs. For platforms employing morphing structures, ADRC control can achieve attitude stabilization in flight mode without requiring precise modeling.

Mode switching control is crucial for achieving smooth multi-modal transitions. Currently, aerial-ground mode switching is often accomplished through foldable arms and the transfer of control authority, while aerial-aquatic transitions frequently rely on underwater thrusters to achieve stable navigation. During mode switching, the system dynamics undergo abrupt changes, and maintaining stability under external disturbances remains a problem worthy of further investigation.

3.3. Cross-Medium Communication and Perception

In terms of environmental perception, existing research often leverages the aerial perspective advantage of UAVs, combining image processing with Kalman filtering to construct elevation-occupancy fused global environment maps, thereby providing a navigation foundation for unmanned ground vehicles. Similarly, three-dimensional grid maps incorporating elevation-occupancy hybrid information are also used to support aerial-ground trajectory planning. Regarding cross-medium communication, underwater communication represents a significant challenge for aerial-aquatic amphibious UAVs. One currently effective solution employs underwater fiber-optic communication technology, utilizing tethered buoys to achieve high-bandwidth, low-loss underwater data transmission, significantly enhancing the communication efficiency of UAVs in deep-water environments.

4. CURRENT MAJOR CHALLENGES

Although significant progress has been made in multi-modal UAV research, several common challenges remain. In terms of system design and lightweighting, multi-mode structures often result in high system redundancy and increased weight, which severely limits endurance and payload capacity. Achieving lightweighting while ensuring structural strength and functional integrity remains a primary design challenge. Regarding the robustness of mode switching, the abrupt dynamic changes at the moment of transition impose extremely high demands on the robustness of control algorithms. Ensuring smooth and reliable switching, particularly under external disturbances such as wind gusts or sudden terrain changes, still requires further investigation.

In terms of energy management and endurance, multi-mode operation leads to higher energy consumption. Although ground or surface modes can partially improve energy efficiency, overall endurance remains a critical bottleneck limiting large-scale application. Novel energy sources (such as hydrogen fuel cells and solar power) and efficient energy management strategies represent important future research directions. Regarding autonomy and intelligent decision-making, most current research still relies on manual remote control or preset missions, with limited autonomous decision-making capabilities. Enabling UAVs to autonomously select the optimal locomotion mode and plan paths based on environmental information such as terrain, obstacles, and remaining battery power is key to achieving true intelligence. Concerning the limitations of cross-medium communication, while underwater fiber-optic communication addresses bandwidth issues, it restricts the operational range. Achieving reliable, tetherless integrated air-water wireless communication remains a technical challenge that urgently needs to be addressed.

5. FUTURE DEVELOPMENT TRENDS

The deep integration of structure and function represents a crucial direction for future development. Researchers are moving beyond simply superimposing different locomotion mechanisms and are instead exploring multifunctional structural reuse to achieve "one machine, multiple uses," thereby further reducing system weight. Intelligent control and autonomous decision-making will leverage artificial intelligence technologies such as deep reinforcement learning to endow multi-modal UAVs with enhanced environmental understanding and autonomous decision-making capabilities, enabling autonomous mode switching and dynamic path planning based on mission requirements and environmental perception.

In terms of swarm operations and collaborative coordination, multi-vehicle collaboration (such as UAV-UGV coordination) can significantly improve mission execution efficiency and coverage. Future research will focus more on the collaborative control and task allocation of heterogeneous robotic systems. The exploration of novel energy sources and propulsion systems is expected to

fundamentally address endurance bottlenecks. High-energy-density solid-state batteries, hydrogen fuel cells, as well as the integration of solar power and wireless charging technologies into UAV platforms, all offer broad research and application prospects. The application of advanced materials and manufacturing processes, such as carbon fiber and 3D printing, will provide greater possibilities for topological optimization, rapid prototyping, and customized design of multi-modal UAV structures, enabling improved strength-to-weight ratios.

6. CONCLUSION

By integrating multiple modes of locomotion—such as aerial, ground, and surface or underwater operations—multi-modal UAVs have transcended the application boundaries of single-mode unmanned systems and have emerged as a vital direction in robotics. This paper systematically reviews research progress in this field from the perspectives of system configuration, key technologies, challenges, and trends. Although numerous challenges remain in areas such as structural lightweighting, robustness of mode switching, energy efficiency, and autonomous decision-making, the continuous advancement of new materials, artificial intelligence, and advanced control theories is driving the evolution of multi-modal UAVs toward greater integration, intelligence, and efficiency. These systems are expected to play an irreplaceable role in future applications, including military reconnaissance, disaster relief, environmental monitoring, and urban logistics.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

- [1] YANG Xingbang, LIANG Jianhong, WEN Li, et al. Research Status of Aerial-Aquatic Amphibious Cross-Domain Unmanned Vehicles[J]. *Robot*, 2018, 40(01): 102-114.
- [2] ZHONG Dichang. Design and Implementation of Control System for Aerial-Ground Amphibious UAV[D]. Nanchang University, 2020.
- [3] ZHANG Xinze, XIAO Haijian, LIU Xinglong, et al. Design and Implementation of a Novel Ducted Fan Aerial-Aquatic Amphibious UAV[J]. *Acta Armamentarii*, 2025, 46(01): 3-13.
- [4] WU Lihua, CAI Zhanda, WU Yunfa, et al. Design and Implementation of Air-Sea UAV Based on Cross-Medium Communication Technology[J]. *Mechanical & Electrical Engineering Technology*, 2025, 54(05): 52-58.
- [5] XU Yang. Research on Path Planning for Unmanned Vehicles Based on Aerial-Ground Integration[D]. Chongqing University of Technology, 2025.
- [6] YU Jialun. Design of Control System for Air-Ground Integrated Reconnaissance Robot[D]. Nanjing University of Science and Technology, 2023.
- [7] ZHANG Zheng, LI Xingwei, ZHAO Xianfa. Research on a Lightweight Aerial-Ground Amphibious Platform with Morphing Structure[J]. *Journal of Ordnance Equipment Engineering*, 2024, 45(07): 105-114.
- [8] LI Zeyu. Control of Aerial-Ground Amphibious Morphing UAV[D]. Guangdong University of Technology, 2022.
- [9] GUO Yongjie. Structural Design and Simulation Analysis of Aerial-Ground Amphibious Individual Soldier UAV[D]. Shenyang Ligong University, 2025.
- [10] LI Jinfang. Structural Design and Function Realization of Aerial-Ground-Aquatic Triphibious UAV[D]. Beijing University of Chemical Technology, 2025.
- [11] LI Kailin, HAN Baoling, LUO Qingsheng, et al. Motion Planning and Simulation of Combined Aerial-Ground Amphibious Robot[J]. *Machinery Design & Manufacture*, 2022, (06): 245-248+253.
- [12] WANG Shuai, XIAO Changjiang, DUAN Songzhi, et al. Structural Design and Mechanical Analysis of a Detachable Aerial-Ground Amphibious Robot Based on Quadrotor Platform[J]. *Mechanical and Electrical Information*, 2025, (17): 44-48.
- [13] ZHONG Peng. Research and Design of Aerial-Aquatic Amphibious Multi-Rotor UAV[D]. Nanjing University of Information Science and Technology, 2021.
- [14] PEI Jieren. Research and Application of Aerial-Ground Amphibious UAV and Its Trajectory Planning Technology[D]. Guangdong University of Technology, 2025.
- [15] LI Xiaolin. Design and Locomotion Mode Study of Aerial-Ground Amphibious Morphing Robot[D]. Jiangsu University of Science and Technology, 2025.