Journal of Marine Science and Application (2026) 25: 1456-1470
https://doi.org/10.1007/s11804-026-00796-8

REVIEW

Review of Hybrid Aerial-Aquatic Vehicles: Bio-Inspired Design and Drone-UUV Integration for Cross-Domain Locomotion Characteristic

Hongde Qin[1], Xin Liu[1], Yifan Xue[1], Yunsai Chen[1] and Zhongben Zhu[1]

Received: 22 April 2025 / Accepted: 07 January 2026
© Harbin Engineering University and Springer-Verlag GmbH Germany, part of Springer Nature 2026

Abstract

With the growing demand for cross-domain operations in fields such as environmental monitoring, emergency response, and scientific exploration, hybrid aerial-aquatic vehicles (HAAVs) have emerged as a cutting-edge research direction integrating bio-inspired principles and multi-domain robotic technologies. This paper systematically reviews the technological trajectories of HAAVs: bio-inspired designs achieve efficient air-water transitions through flapping-wing (e. g., flying fish/insect-inspired) and water-jet (e. g., cephalopod-inspired) propulsion systems, enhanced by morphing structures (e.g., bistable airfoils, foldable wings). Meanwhile, drone-UUV integrated systems employ unimodal (multirotor/fixed-wing) and multimodal architectures, optimizing multi-domain adaptability through hybrid thrust mapping and active buoyancy control. Key challenges remain in cross-medium dynamic coupling, energy efficiency, and communication reliability. This paper provides theoretical foundations and technical roadmaps for the bio-inspired design and system integration of next-generation intelligent cross-domain platforms.

Keywords Hybrid aerial-aquatic vehicles; Bio-inspired design; Drone-UUV integration; Cross-domain locomotion

1 Introduction

Hybrid aerial-aquatic vehicles (HAAVs), exhibiting multimodal operational capabilities across aquatic and aerial domains, represent a prominent research domain experiencing accelerated development through synergistic integration of aerospace systems engineering, and autonomous robotics. These HAAVs demonstrate transformative potential for mission-critical applications spanning ecological surveillance, emergency response coordination in maritime environments, and strategic reconnaissance operations requiring seamless air-water transition capabilities. Technological development of HAAVs originates from early 20th-century experimental prototypes like the Reid Flying Submarine (RFS-1), a pioneering demonstration of submersible flight mechanics. Contemporary advancements in composite materials, hybrid propulsion systems, and intelligent control architectures have fundamentally transformed the design paradigm of HAAVs, facilitating robust performance adaptation in dynamic multi-domain environments.

Recent research in HAAVs is bifurcated into two principal methodologies: biomimetic mechanisms and drone-UUV integration. Biomimetic designs emulate the locomotion strategies of amphibious organisms, such as flying fish and cephalopods, to achieve efficient propulsion and maneuverability. For instance, bio-inspired flapping-wing systems (e.g., MIT's flying fish robot) employ undulatory thrust generation with active oscillation control, enabling dynamic thrust modulation, while water-jet mechanisms (e.g., Imperial College's squid-inspired propulsion) leverage fluid dynamics for high-speed aquatic-aerial transitions. As critical functional components, morphing mechanisms based on bistable airfoils and foldable wing configurations significantly enhance the topological reconfiguration capability of transmedium vehicles through dynamic optimization of aero-hydrodynamic coupling characteristics. Parallel advancements in drone-UUV hybrid systems focus on modular architectures, where unimodal configurations and multimodal platforms integrate heterogeneous propulsion

Article Highlights

- Bio-Inspired Propulsion Systems: Innovative flapping-wing and water-jet mechanisms, inspired by organisms like flying fish and squids, enable efficient air-water transitions and adaptive multi-domain locomotion.
- Drone-UUV Hybrid Architectures: Integration of aerial drones and underwater vehicles through unimodal and multimodal systems, optimizing cross-domain performance via hybrid thrust mapping and active buoyancy control.

✉ Yifan Xue
xueyifan@hrbeu.edu.cn

[1] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

and buoyancy control to balance operational simplicity with functional diversity.

Notwithstanding these advances, significant challenges still exist. Cross-medium dynamic coupling contributes to nonlinear hydrodynamic and aerodynamic interactions that challenge conventional control frameworks particularly during rapid air-water transitions. Energy efficiency remains a bottleneck, as dual-domain operation imposes divergent power demands. Moreover, robust air-water communication requires novel approaches to address signal attenuation and latency. Addressing these issues requires interdisciplinary collaboration, spanning biomechanics, fluid dynamics, and embedded systems engineering. This paper synthesizes the state-of-the-art in HAAVs research, systematically analyzing design principles, technological implementations, and unresolved challenges.

This review is based on a systematic search of major academic databases, including Web of Science, Scopus, and IEEE Xplore. Key search terms such as "hybrid aerial-aquatic vehicle", "hybrid aerial underwater vehicle" were employed. The literature was screened for relevance to HAAVs design and multimodal locomotion, with a focus on peer-reviewed articles from the past decade that demonstrate a obviously increase in publication volume, reflecting the field's growing research activity.

The remainder of this paper is organized as follows: Section 2 describes the design inspirations for HAAVs: bio-inspired and drone-UUV integration. Section 3 reviews bio-inspired mechanisms, categorizing them into flapping-wing, water-jet, and deformation types. Section 4 reviews drone-UUV integrated systems, divided into unimodal and multimodal types. Section 5 provides a comparative analysis of the two major design paradigms, discussing their respective trade-offs. Section 6 expounds key research challenges in dynamics control, energy management, and adaptive propulsion. Finally, Section 7 concludes the review and suggests future research directions.

2 Design inspiration of HAAV

The concept of a vehicle capable of traversing both air and water can be traced back to the Reid Flying Submarine (RFS-1), conceived by Donald V. Reid in the 1930s. This groundbreaking design laid the foundation for HAAVs, capable of operating seamlessly in diverse environments. Post-WWII breakthroughs in aviation and submarine technologies materialized Reid's vision, enabling the RFS-1 to conduct transmedium missions featuring aquatic takeoff, aerial flight, and limited underwater navigation (Reid, 2012). These developments marked a pivotal breakthrough in HAAVs evolution, validating the viability of merging aerial and aquatic capabilities within a single airframe. The 21st-century convergence of automation and robotics has driven transformative advances in HAAV development, powered by advanced autonomous systems such as aerial drones, unmanned underwater vehicles (UUVs), AUVs, and ROVs. These innovations have expanded HAAVs capabilities by improving operational agility, energy efficiency, and autonomous decision-making, enabling diverse cross-domain applications.

Currently, the development of HAAVs is guided by two primary design paradigms. As shown in Figure 1, the first approach employs biomimetics, utilizing evolutionary adaptations from amphibious organisms like cliff puffins, flying fish, and frilled squids. By replicating their biomechanical efficiencies, this strategy enhances HAAV performance across aerial and aquatic domains, achieving optimized maneuverability and energy efficiency. The second approach focuses on the integration of drone and UUV technologies shown in Figure 1, utilizing modular propulsion systems and adaptive configurations to facilitate seamless air-water transitions. This method emphasizes technological synergy, enabling HAAVs to harness the complementary strengths of aerial and underwater platforms. 3nics, aerospace engineering, and autonomous systems to expand transmedium operational capabilities.

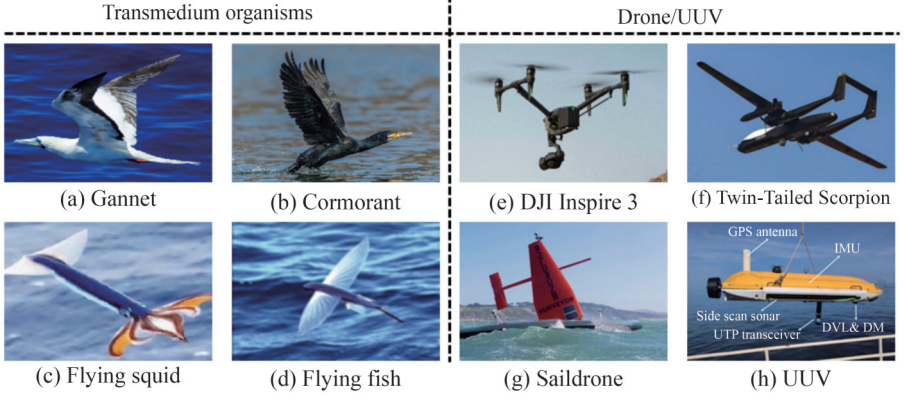


Figure 1 Design inspiration of HAAV (a) Gannet (Wang et al., 2024b) (b) Cormorant (Dong et al., 2017) (c) Flying squid (Hou et al., 2020) (d) Flying fish (Gao and Techet, 2011) (e) DJI Inspire3 (DJI Inspire3, 2025) (f) Twin-Tailed Scorpion (TWIN-TAILED SCORPION, 2017) (g) Saildrone (Saildrone Surveyor, 2025) (h) UUV (Bao et al., 2025)

3 Biomimetic mechanism based HAAV

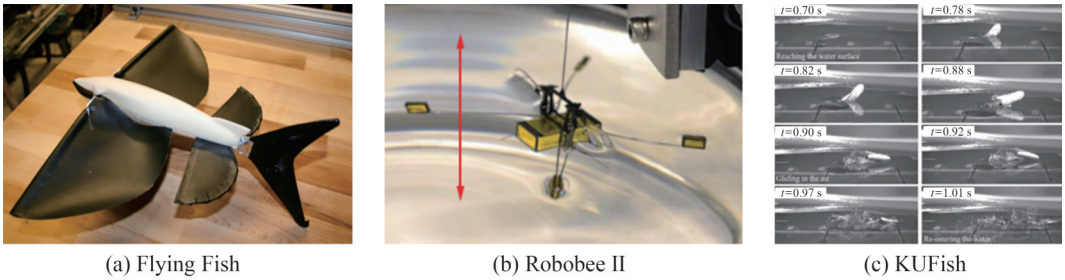
Based on the propulsion mechanism, bio-inspired HAAVs can be classified into two primary categories: 1) Flapping-wing type, which generates propulsion through the rhythmic flapping or oscillatory motion of wing-like or fin-like structures. This design emulates the locomotion mechanisms of birds, insects, and aquatic organisms, enabling efficient mobility in both aerial and aquatic environments. 2) The water-jet type, which utilizes fluid expulsion from an internal chamber for propulsion, is a mechanism inspired by marine species such as squid. This approach is particularly effective for achieving high-speed thrust in aquatic environments while retaining the capability for aerial flight transitions. Moreover, some bio-inspired HAAVs integrate bio-inspired morphing structural designs, enabling dynamic shape or configuration adjustments to optimize cross-domain performance. For example, wing-like or fin-like structures can dynamically adjust their geometry to enhance aerodynamic lift during flight or improve hydrodynamic efficiency underwater. These morphing capabilities are often inspired by the adaptive traits of organisms, such as flying fish that adjust their fins for gliding or birds that modify wing morphology during various flight phases to optimize flight performance. By integrating such morphing features, HAAVs achieve significantly enhanced versatility and energy efficiency in complex multi-domain environments. As shown in Table 1, this classification and design framework emphasizes the diversity of bio-inspired propulsion strategies while highlighting the pivotal role of adaptive structures in enabling seamless transitions between aerial and aquatic operations.

3.1 Flapping-wing type

Gao and Techet (2011) developed an aerial-aquatic robotic vessel inspired by the biomechanics of flying fish shown in Figure 2(a). The operational principles of the robot are as follows: underwater, it utilizes tail oscillation for propulsion, mimicking the undulatory swimming motion of fish. During the transition from water to air, the tail generates sufficient upward thrust to propel the robot out of the water. Upon achieving airborne status, the robot deploys its wing-like appendages to enable transient gliding. However, the prototype's measured water-exit velocity of only 2.84 m/s reached merely 24% of the theoretical minimum speed (11.87 m/s) required for sustained aerodynamic gliding. This critical velocity gap fundamentally restricted its airtime, highlighting a core challenge in achieving seamless transmedium mobility. As shown in Figure 2(b), Harvard University proposed an insect-scale HAAV named Robobee II. In this research, a lightweight and controllable driving system has been designed that allows for the seamless transition between the air and underwater environments, which is aimed at resolving the issues arising from the disparities in power requirements and resistance that

Table 1 Summary of Bio-inspired HAAVs

Type	Name	Key mechanism/Features	Mass
Flapping-wing	Robotic Flying Fish (Gao and Techet, 2011)	Tail oscillation propulsion + aerial gliding	145 g
	Robobee II (Chen et al., 2017)	Electromagnetic flapping-wing + seawater electrolysis for buoyancy	175 mg
	KUFish (Nguyen and Park, 2023)	Tail-beating propulsion + dual-mode water-air transition	116 g
Water-jet	Squid-inspired HAAV (Siddall et al., 2017)	Micro-piston water-jet propulsion	100 g
	Jump-glide HAAV (Zufferey et al., 2019)	Lithium-water reaction gas jet + gliding	160 g
	Flying-squid HAAV (Hou et al., 2020)	Soft morphing fins + gas-liquid isolation jet	1.12 kg
Deformation	Bionic-Gannet (Liang et al., 2013)	Wing folding reduces water entry impact; mimics plunge-diving	7.2 kg
	Morphing Airfoil HAAV (Gu et al., 2024)	Switchable symmetric/asymmetric airfoils	1.8 kg
	Dipper (Rockenbauer et al., 2021)	Foldable wing reduces hydrodynamic drag	3.1 kg
	AquaMAV (Siddall et al., 2017)	Three-section folding wing + water-jet assist	201.3 g
	Longbow II (Sun et al., 2023)	Foldable wing + multi-cycle water-air transition	13.3 kg



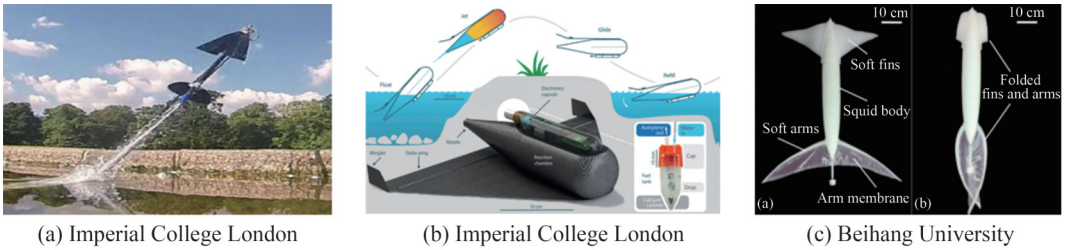
(a) Flying Fish (b) Robobee II (c) KUFish

Figure 2 Flapping-wing HAAVs (a) Flying Fish from Massachusetts Institute of Technology (Gao and Techet, 2011) (b) Robobee II from Harvard University (Chen et al., 2017) (c) KUFish from Konkuk University (Pham et al., 2023)

the Robobee's driving system encounters when operating in different media, namely air and water. The fundamental principle behind this system is that it takes advantage of the process of electrolyzing seawater, through which H_2 and O_2 are generated to offer the necessary buoyancy. Robobee II drives a miniature electromagnetic coil actuator through periodic current pulses to generate an electromagnetic field, which then drives the wings to flap. This electromagnetic drive system, which features light weight and high efficiency, can flap the wings at a high frequency, generating sufficient lift to support flight in the air. Moreover, when the Robobee II enters the underwater environment, it will adjust the flapping frequency to adapt to the higher resistance in water, thus achieving underwater propulsion. The experiments were conducted in freshwater under static conditions, using tap water (with surfactant added) at ambient temperature (Chen et al., 2017). In 2023, Konkuk University developed KUFish shown in Figure 2(c), a bio-inspired robotic fish mimicking flying fish locomotion mechanisms. The robot features a tail-beating propulsion system for efficient underwater navigation, enabling precise and energy-effective movement in aquatic environments. Additionally, the KUFish demonstrates dual-mode functionality by transitioning from underwater swimming to aerial gliding after water exit, closely replicating the natural behavior of flying fish. This capability underscores its seamless operational adaptability across aquatic and aerial domains, showcasing significant advancements in bio-inspired transmedium robotics (Nguyen and Park, 2023; Pham et al., 2023).

3.2 Water-jet type

Siddall and Kovač (2017) designed a HAAV inspired by the jet-propulsion mechanisms of cephalopods such as squids and cuttlefish shown in Figure 3(a). The robot employs a water-jet propulsion system incorporating a compression chamber housing a micro piston or plunger. The piston, actuated by a precision-controlled micromotor or electromagnetic drive, serves as the core component for generating propulsion. When rapidly retracted, the piston pressurizes water within the chamber, ejecting a high-velocity jet through a nozzle to produce reactive thrust, thereby enabling forward locomotion. In addition, Imperial College London developed a jump-glide HAAV, shown in Figure 3(b) utilizing aqueous-reactive chemical fuel (e.g., lithium-water reactions) to power its propulsion system. The HAAV employs controlled exothermic reactions between lithium and water to rapidly generate gas, which pressurizes a combustion chamber. This pressurized gas is subsequently expelled through a nozzle, producing thrust to propel the robot into a jump phase. Following aerial ascent, the HAAV transitions into a gliding mode, enabling sustained flying locomotion through iterative jump-glide cycles (Zufferey et al., 2019). Hou et al. (2019a, 2019b, 2020) developed a flying-squid-inspired aquatic-aerial vehicle featuring soft morphing fins and arms shown in Figure 3(c). In the bionic mantle cavity, a silicone membrane is employed as a gas-liquid isolation layer. During the jetting process, the compressed gas from the gas cylinder pressurizes the cavity, causing the gas-liquid isolation layer to move backward, thereby expelling water through the jet orifice. The morphing structure of this HAAV achieves shape transformation via the expansion and contraction of inflatable cavities, significantly reducing redundant mechanical components. Based on the above-mentioned propulsion system of the bio-inspired water-jet HAAV, Wang et al. (2023) proposed an explosive water-jet thruster based on butane (C_4H_{10}) and oxygen (O_2). A single fuel unit can support more than 50 explosions without the need to replace components or rely on external gases. This thruster achieves high-thrust and repeatable continuous underwater propulsion, providing an important technological breakthrough for HAAVs. In addition, Wang et al. (2024a) designed a novel water-jet thruster named CM-jet by combining the cavity-based water-jet (C-jet) structure and the membrane-based water-jet (M-jet) structure. Based on the traditional C-jet structure, the CM-jet structure adds a flexible membrane. The membrane is located inside the cavity, separating the water from the high-pressure gas. Due to the isotropic elastic deformation of the membrane, the CM-jet structure can generate stable propulsion forces in any direction, without being affected by the launch angle. This design enables the CM-jet structure to achieve multi-degree-of-freedom propulsion in a three-dimensional space.



(a) Imperial College London (b) Imperial College London (c) Beihang University

Figure 3 Water-jet HAAV (a) Water-Jet HAAV from Imperial College London (Siddall and Kovac, 2017) (b) Jump-glide HAAV based on water-reactive fuel from Imperial College London (Zufferey et al., 2019) (c) Squid-like aquatic-aerial vehicle with soft morphing fins and arms from Beihang University

3.3 Deformation type

Inspired by the bio-inspired principles of manta rays (aquatic) and eagles (aerial), Gu et al. (2024) developed a bio-inspired wing with bistable morphing airfoils for aquatic-aerial robots shown in Figure 4(a). This wing integrates a symmetric airfoil (NACA0012) for underwater operation and an asymmetric airfoil (NACA7412) for aerial flight. In aquatic mode experiments, the symmetric airfoil (NACA0012) exhibited superior adaptability to aquatic environments, achieving an average lift-to-drag ratio (L/D) of 3.864 at angles of attack (AOA $\geqslant 2°$). In aerial mode experiments, the asymmetric airfoil (NACA7412) demonstrated optimized aerodynamic efficiency for low-speed flight, with a peak L/D reaching 4.045 at low angles of attack (AOA $< 8°$), making it suitable for flight due to its optimized aerodynamic efficiency. This dual-mode design validates the effectiveness of bistable morphing airfoils in enhancing cross-media adaptability for hybrid aquatic-aerial robotic systems.

In response to the plunge-diving motion of gannets, Liang et al. (2013) designed an amphibious cross-domain vehicle named Bionic-Gannet I shown in Figure 4(b). Structurally, the bionic gannet's main body is constructed using an aluminum frame to mount measurement devices and support a streamlined housing. The housing, shaped to mimic a gannet's morphology, is fabricated from carbon-fiber-reinforced plastic (CFRP). The wings are connected to support arms via three longitudinal carbon fiber rods, with the support arms rotating around fixed axes to drive wing folding. To replicate the wing-folding mechanism, a morphing variable-swept wing (MVSW) mechanism was developed. By adjusting the position of sliders along guide rails, this mechanism achieves adjustable wing sweep angles.

Wang et al. (2013) designed a HAAV named Bionic-Gannet II by mimicing the plunge-diving behavior of gannets shown in Figure 4(c). Based on morphological data from real gannets, a simplified bionic model (Bionic-Gannet) was developed for finite element simulation analysis. The influence of the feet was neglected, and the wing sweepback angle was fixed at 86°. The simulation results indicate that the impact acceleration during water entry is quadratically proportional to the initial velocity. Vertical water entry (90°) can avoid lateral force-induced damage but results in higher longitudinal acceleration.

Rockenbauer et al. (2021) developed a foldable fixed-wing water-air HAAV named Dipper shown in Figure 4(d). The Dipper enhances its dynamic performance in multi-media environments through dynamic air-water transitions enabled by its foldable wing. This innovative design allows Dipper to optimize its aerodynamic and hydrodynamic properties during medium transitions, ensuring efficient and stable operation in both aerial and aquatic environments. The foldable wing mechanism significantly reduces water-entry resistance and facilitates rapid adaptation to changing operational conditions, demonstrating the HAAV's versatility in transmedium applications.

Siddall et al. (2017) designed a morphing aquatic micro air vehicle featuring a conventional fixed-wing layout shown in Figure 4(e), a V-shaped tail, and a three-section wing capable of folding backward by 90°. This folding mechanism allows the vehicle to rapidly reduce water-entry resistance when transitioning from aerial to aquatic modes. Additionally, the HAAV is equipped with a secondary power source in the form of a water-jet propulsion system, which enhances its water-exit speed by providing additional thrust during the transition back to aerial flight. This dual-power design ensures efficient and rapid medium

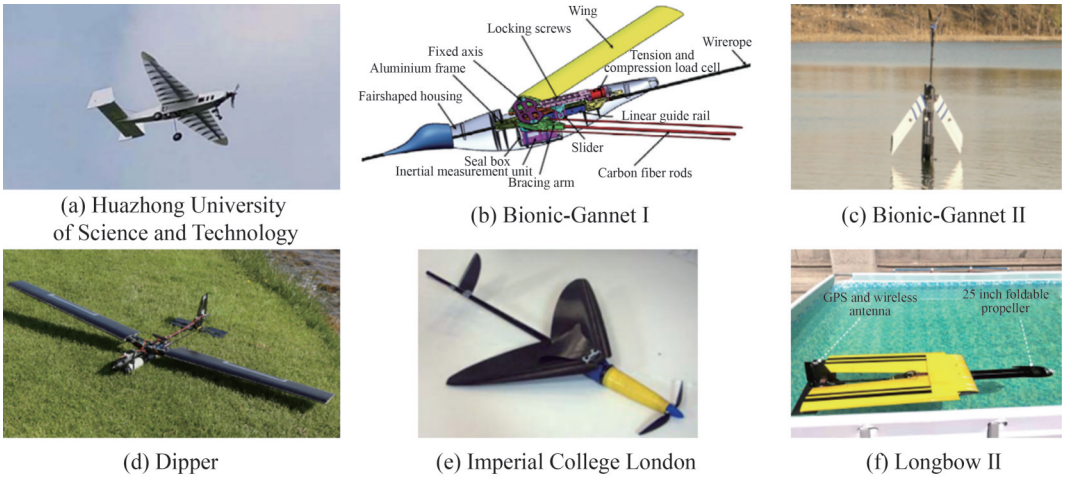


Figure 4 Biomimetic-deformation HAAV (a) Aquatic-Aerial Robots With Bistable Morphing Airfoil from Huazhong University of Science and Technology (Gu et al., 2024) (b) Bionic-Gannet I from Beihang University (Liang et al., 2013) (c) Bionic-Gannet II from Beihang University (Wang et al., 2013) (d) Dipper from ETH Zurich (Rockenbauer et al., 2021) (e) Morphing aquatic micro air vehicle from Imperial College London (Siddall et al., 2017) (f) Foldable wing unmanned aerial-underwater vehicle named Longbow II from Harbin Engineering University (Sun et al., 2023)

transitions, optimizing the HAAV's performance in both aerial and aquatic environments.

Sun et al. (2023) developed a foldable-wing unmanned aerial-underwater vehicle (UAUV), named Longbow II shown in Figure 4(f), capable of executing both underwater diving and aerial flight missions. This UAUV is designed to perform multi-cycle water-air transitions while carrying mission with payloads during a single deployment. Its foldable-wing mechanism reduces hydrodynamic drag during underwater navigation and water-exit phases, while the post-exit deployed fixed wings provide aerodynamic lift for sustained flight. Field tests were performed in a freshwater lake and a test pool, with natural wave disturbance. Quantified data on salinity, specific temperature range, and turbulence levels during the tests were not reported. During the water-exit phase, the UAUV must operate at elevated velocities and substantial pitch angles to overcome the coupled nonlinear hydrodynamic-aerodynamic interactions. To address these challenges, Han et al. (2024) established a scaled experimental framework, constructing high-fidelity hydrodynamic models via structural drainage analogies and implementing a dual-track test platform for quantitative performance validation. Building on this, Sun et al. (2024) proposed a relay computational methodology to predict water-exit dynamics and post-transition flight behavior. This approach integrates multi-domain coupling dynamics, including interfacial force discontinuities during water-air transitions, wing-deployment-induced load variations, and post-exit attached-water effects. The methodology combines an efficient aerodynamic coefficient identification algorithm with a novel approach for attached-water state characterization, enabling high-precision modeling of transient transmedium phenomena.

4 Drone-UUV based HAAV

Based on the body-configuration integration of drones and UUVs, HAAVs can be classified into two primary categories: 1) Unimodal HAAVs, predominantly adopting quadrotor or fixed-wing drone configurations, which employ a unified dynamic model to operate in both underwater and aerial environments shown in Table 2. 2) Multimodal HAAVs, typically integrating two or more configurations (e.g., quadrotor drones, fixed-wing drones, and multi-degree of freedom UUVs) to achieve adaptive switching between underwater and aerial locomotion modes through the integration of multiple power systems or morphing mechanisms shown in Table 3. This classification framework

Table 2 Summary of Unimodal type HAAVs

Type	Institution	Key Mechanism/Features	Mass
Multi-Rotor	Oakland University (Alzu'bi et al., 2018)	Active buoyancy control + unified propulsion	2.7 kg
	Rutgers University (Maia et al., 2017)	Octocopter + hierarchical control system	3.85 kg
	Beihang University (Li et al., 2023)	Remora-inspired adhesion + triboelectric sensors	2.4 kg
	UC Berkeley (Zha et al., 2019)	PWM-thrust mapping + three-phase transition protocol	202 g
	Harbin Institute of Technology (Tan et al., 2023)	Active disturbance rejection control (ADRC)	5 kg
Fixed-wing	Johns Hopkins University (Moore et al., 2018)	Underwater-capable propeller + delta-wing planform	100 g
	NC State University (Weisler et al., 2018)	Rotary-wing takeoff + fixed-wing cruise	160 g
	NC State University (Stewart et al., 2018)	Water-jet assisted takeoff + dual-motor system	1.12 kg

Table 3 Summary of Multimodal HAAVs

Name	Key Mechanism/Features	Mass
Morphable aerial-aquatic quadrotor (Tan and Chen, 2020)	Single thruster rotates around arm for mode switching	500 g
TJ-FlyingFish (Liu et al., 2023)	Dual-speed gearbox + reversible propeller rotation	1.63 kg
Mirs-Alioth (Huang et al., 2024a)	Singular thrust tilt angle (STTA) control for underwater leveling	700 g
Submersible unmanned flying boat (Yao et al., 2014)	Variable swept-wing + dual propulsion (aerial propeller & water-jet)	12 kg
Nezha III (Lu et al., 2021)	Pneumatic buoyancy system + foldable arms	14.68 kg
Nezha-Mini (Bi et al., 2022a)	Compact design (A4 size); integrates quadrotor and 3-DoF UUV	953 g
Nezha-F (Bai et al., 2023)	Novel arm mechanism integrated with Piston-driven VBS (PVBS)	1.25 kg
Nezha-IV (Jin et al., 2023)	Four aerial propellers + eight underwater thrusters	21 kg
Nezha-B (Bi et al., 2024)	Double-layered staggered quadrotor + streamlined hull	900 g
Nezha-SeaDart (Jin et al., 2024)	Capable of VTOL from land/water; wing-generated lift for cruising	1.5 kg
Diving hawk (Wang et al., 2024c)	Two tilt rotors + one fixed rotor; movable buoyant tailplane	8.9 kg

emphasizes the evolving design paradigms of HAAVs, balancing structural simplicity with functional versatility for cross-domain mission adaptability.

4.1 Unimodal type

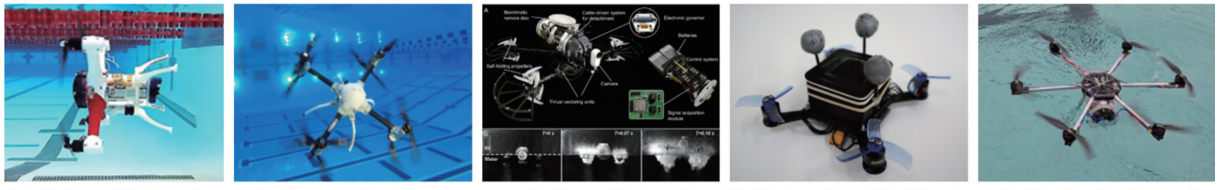
Alzu'bi et al. (2018) designed a hybrid unmanned aquatic-aerial quadcopter equipped with active buoyancy control shown in Figure 5(a). The vehicle employs a unified set of motors and propellers for both aerial flight and underwater propulsion, enabling seamless transitions between water and air. Buoyancy and underwater depth are regulated through a ballast system, ensuring precise control during underwater operations. For stability and maneuvering in aerial and surface modes, a closed-loop control algorithm is implemented, while an open-loop control algorithm is utilized for underwater navigation. This dual-control approach optimizes the vehicle's performance across diverse operational environments, demonstrating its adaptability and efficiency in transmedium applications.

Maia et al. (2017) and Villegas et al. (2017) developed a multirotor aerial-underwater vehicle named Navigator, featuring an eight-axis quadrotor configuration shown in Figure 5(b). The vehicle employed a hierarchical control system for attitude tracking, integrating a proportional control law in series with a body angular rate proportional-integral-derivative (PID) controller. Height stability was maintained using a PID controller with restoring force compensation, while a gain-scheduling strategy was implemented to manage transitions between aerial and aquatic environments. Subsequently, Ravell et al. (2018) formulated a continuous dynamics model for the vehicle using the Newton-Euler equation, incorporating the effects of buoyancy and hydrodynamic drag. A hybrid control system was designed for trajectory tracking, which included a transition strategy to ensure smooth switching between media, further enhancing the vehicle's operational versatility.

Li et al. (2023) introduced an aerial-aquatic hitchhiking robot featuring a double-layer quadrotor configuration shown in Figure 5(c). The robot's hitchhiking mechanism is inspired by the mechanoreceptors of the remora (Echeneis naucrates) disc and incorporates two flexible bioinspired tactile sensors (FBTS) based on triboelectric nanogenerator technology. These sensors enable precise tactile sensing of attachment status, enhancing the robot's ability to adhere to and interact with various surfaces during transmedium operations. This innovative design leverages biomimetic principles to improve the robot's adaptability and functionality in both aerial and aquatic environments.

As shown in Figure 5(d), Zha et al. (2019) designed a 202-gram mini UAUV. Through experimental measurements, they established the mapping relationships between the input Pulse Width Modulation (PWM) signals, motor speed, and thrust for the UAUV's electronic speed controller and brushless motor in both air and water. A three-step transition protocol was proposed as follow. Underwater Acceleration: Based on the underwater command-thrust mapping, the mini UAUV accelerates towards the water surface from underwater, during which a depth estimator tracks its vertical position and velocity. Water-Air Transition: Upon entering the transition zone, a timer is initiated because depth estimation becomes unreliable. By establishing a force balance equation in the vertical direction, the time window for the propellers to emerge into the air is estimated. The system switches to the aerial command-thrust mapping when the timer falls within this window and all propellers are exposed to the air. Aerial Flight: After the water-air transition, the mini UAUV operates according to the aerial command-thrust mapping for flight. This strategy ensures a smooth and controlled transition from underwater to aerial operation, leveraging precise mappings and estimations to maintain stability and performance across different mediums.

To address challenges including time-varying model parameters, complex hydrodynamic forces, and external disturbances (e. g., water currents, wind, and waves) in amphibious multi-rotor unmanned aerial vehicles (UAVs) shown in Figure 5(e), Tan et al. (2023) developed an Active Disturbance Rejection Control (ADRC)-based strategy for out-of-water motion control. A cascade ADRC control architecture was designed, incorporating an Extended State Observer (ESO) to estimate and compensate for system disturbances in real time. Experimental results demonstrated that the ADRC controller achieved minimal atti-



(a) Oakland University (b) Rutgers University (c) Beihang University (d) University of California, Berkeley (e) Harbin Institute of Technology

Figure 5 Unimodal Multi-Rotor-Drone HAAVs (a) Hybrid unmanned aquatic-aerial quadcopter from Oakland University (Alzu'bi et al., 2018) (b) Multirotor aerial-underwater vehicle named navigator from Rutgers University (Maia et al., 2017; Villegas et al., 2017) (c) Aerial–aquatic hitchhiking robot from Beihang University (Li et al., 2023) (d) Mini Unmanned Aerial Underwater Vehicle from University of California, Berkeley (Zha et al., 2019) (e) Water and air amphibious multi-rotor UAV from Harbin Institute of Technology (Tan et al., 2023)

tude oscillations (roll/pitch angles within ±5°) during the cross-media transition phase, while the PID controller exhibited overshoot (0.2 m) and excessive oscillations, which significantly increased the risk of system instability and control failure.

Moore et al. (2018) designed a fixed-wing unmanned aerial aquatic vehicle that employs an aircraft propeller and electric motor to achieve water-to-air transitions shown in Figure 6(a). Through dimensionless analysis of propeller thrust coefficient, Reynolds number, advance ratio, and Mach number, the study demonstrated that propellers optimized for aerial use retain effective underwater propulsion capabilities. Compared to rotorcraft, the fixed-wing configuration exhibits superior endurance and buoyancy utilization efficiency. The vehicle's delta-wing planform characterized by a unique aerodynamic design, maximizes buoyancy support during water-to-air transitions, enhancing operational stability and energy efficiency. As shown in Figure 6(b), Weisler et al. (2018) designed a fixed wing cross-domain unmanned vehicle. According to the requirements of different operation phases, the vehicle makes use of rotary-wing lift during the water-to-air transition phase. It rapidly drains water and ascends to the flight altitude by means of vertical orientation and a high-thrust propulsion system. During the flight phase, it shifts to horizontal fixed-wing flight, aiming to achieve the maximum range and endurance. Stewart et al. (2018, 2020) developed a seabird-inspired fixed-wing hybrid UAV-UUV system shown in Figure 6(c). The propulsion system incorporates two functionally distinct components. During the water-to-air phase, a waterjet propulsion system supplies supplementary thrust by rapidly expelling water from the variable buoyancy system (VBS) tanks, thereby generating the necessary launch momentum. For the aerial and underwater cruising phases, dual electric motors are utilized: one is optimized for aerial propulsion, while the other is designed for subaquatic locomotion. This configuration ensures sustained power delivery across the vehicle's different operational environments. Young (2014) designed an UAUV named Test Sub II shown in Figure 6d, featuring a low-drag axi-symmetric hull configuration, a detachable mid-mounted wing, and a cruciform tail assembly. In addition, Edwards et al. (2017) designed and developed a multi-modal unmanned vehicle named Test Sub 3 (Flying Sea Glider) shown in Figure 6(e), capable of operating both in aerial flight and underwater gliding. To enable underwater gliding operation, the original propulsion systems including the brushless propulsion motor, electronic speed controller, air-bladder buoyancy control system, and separate battery pressure vessel were removed. A piston-based buoyancy control system was subsequently integrated into the vehicle to enhance underwater propulsion and buoyancy management.

4.2 Multimodal type

As shown in Figure 7(a), Tan and Chen (2019, 2020) developed a morphable aerial-aquatic quadrotor featuring a single thruster capable of rotating around its arm. The tilt angle β of the thruster defines its operational state: when $\beta = 0$, the system operates in lateral mode, with thruster inputs primarily influencing surge, sway, and yaw motions. Conversely, when $\beta = \pm\pi/2$, the system transitions to aerial or diving modes, with thruster inputs predominantly affecting heave, roll, and pitch. This innovative design enables the quadrotor to adapt its propulsion dynamics for both aerial and aquatic environments, enhancing its versatility in transmedium operations. Liu et al. (2023) designed an aerial-aquatic quadrotor named TJ-FlyingFish shown in Figure 7(b), featuring tiltable propulsion units. The propulsion system employs a motor-driven dual-speed gearbox to operate a single propeller, with forward rotation optimized for aerial flight and reverse rotation enhanced by increased torque for aquatic propulsion. Thrust vector control is achieved through the independent rotation of each propulsion unit, enabling precise maneuverability and efficient transitions between aerial and aquatic environments. This innovative design enhances the vehicle's versatility and performance in transmedium operations. As shown in Figure 7(c), Huang et al. (2024a, 2024b) conducted research on the underwater leveling motion control of a morphable unmanned aerial-aquatic vehicle (M-UAAV) named Mirs-Alioth, proposing the Aqua Slide scheme to achieve motion control by leveraging singularity characteristics. The Aqua Slide scheme utilizes the singular thrust tilt angle (STTA) to enable underwater leveling motion for the M-UAAV.



(a) Johns Hopkins University (b) North Carolina State University (c) North Carolina State University (d) U.S. Naval Research Laboratory (e) U.S. Naval Research Laboratory

Figure 6 Unimodal Fixing-Wing-Drone HAAV (a) Fixed-wing unmanned aerial aquatic vehicle from Johns Hopkins University (Moore et al., 2018) (b) Fixed wing cross-domain unmanned vehicle from North Carolina State University (Weisler et al., 2018) (c) Seabird-inspired fixed-wing hybrid UAV-UUV system from North Carolina State University (Stewart et al., 2018) (d) Unmanned Aerial to Underwater Vehicle named Test Sub II from U. S. Naval Research Laboratory (Young, 2014) (e) Flying Sea Glider named Test Sub III from U. S. Naval Research Laboratory (Edwards et al., 2017)

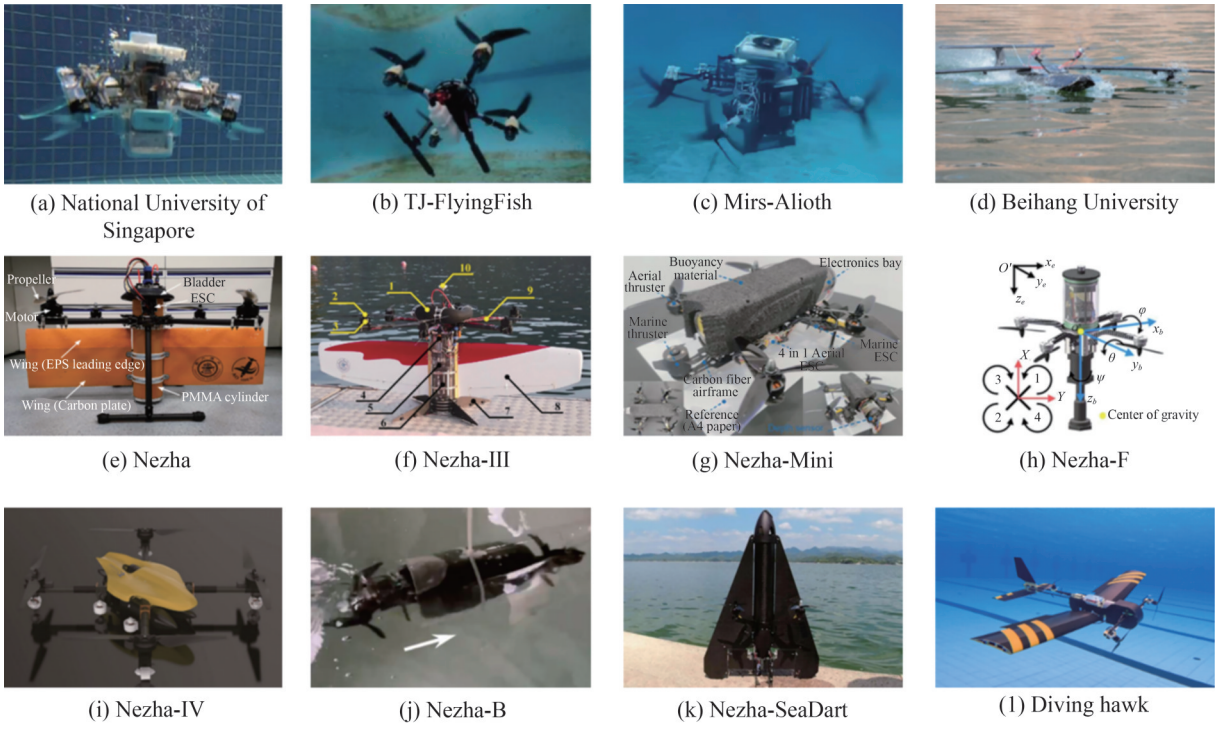


Figure 7 Multimodal HAAVs (a) Morphable aerial-aquatic quadrotor from National University of Singapore (Tan and Chen, 2020) (b) Aerial-aquatic quadrotor with tiltable propulsion units named TJ-FlyingFish from Tongji University (Liu et al., 2023) (c) Morphable unmanned aerial-aquatic vehicle named Mirs-Alioth from Chinese University of Hong Kong (Huang et al., 2024b) (d) Submersible Unmanned Flying Boat from Beihang University (Yao et al., 2014) (e) Multi-mode hybrid aerial underwater vehicle named NEZHA from Shanghai Jiao Tong University (Lu et al., 2019) (f) Multimodal hybrid aerial underwater vehicle named Nezha III from Shanghai Jiao Tong University (Lu et al., 2021) (g) Low-cost hybrid aerial underwater vehicle named Nezha-Mini from Shanghai Jiao Tong University (Bi et al., 2022a) (h) Foldable and self-deployable HAUV named Nezha-F from Shanghai Jiao Tong University (Bai et al., 2023) (i) Hybrid aerial underwater vehicle named Nezha-IV from Shanghai Jiao Tong University (Jin et al., 2023) (j) Bone-shaped hybrid aerial underwater vehicle named Nezha-B from Shanghai Jiao Tong University (Bi et al., 2024) (k) Tail-sitting fixed-wing vertical takeoff and landing hybrid aerial underwater vehicle named Nezha-SeaDart from Shanghai Jiao Tong University (Jin et al., 2024) (l) Multimodal Tilt-Rotor Unmanned Aerial-Aquatic Vehicle named Diving Hawk from Sun Yat-sen University (Wang et al., 2024c)

Through Gazebo-HITL simulations and physical experiments, the effectiveness of the Aqua Slide scheme in addressing critical challenges including control directional uncertainty, coupling effects, and STTA variations was validated. During the control process, the attitude angles (roll and pitch) remained within a maximum deviation of 5°, demonstrating robust stability under complex hydrodynamic interactions and mode transitions. Yao et al. (2014) developed a Submersible Unmanned Flying Boat shown in Figure 7(d). The motion modes of this vehicle are divided into flying boat mode and submarine mode, encompassing six distinct states: aerial flight, surface floating, submergence, underwater cruising, ascending, and emerging from water. A variable swept-wing mechanism was designed, utilizing a lead screw-slider device to achieve the deployment and folding of the wings, thereby adapting to the different requirements of aerial flight and underwater cruising. For aerial flight, a dual-propeller propulsion system was employed, while underwater cruising was facilitated by a water-jet propulsion system driven by a centrifugal pump. As shown in Figure 7(e), Lu et al. (2018), Lu et al. (2019), Wei et al. (2022a, 2022b), Wei et al. (2023) proposed a multimodal hybrid aerial underwater vehicle (HAUV) named NEZHA, integrating underwater gliders (UGs), multirotors and fixed-wing unmanned aerial vehicles (UAVs). High-fidelity simulations of underwater gliding, vertical takeoff, and forward flight validated the vehicle's operational feasibility. The NEZHA HAUV achieves seamless transitions between three operational modes: underwater gliding, multirotor hovering and fixed-wing cruising, demonstrating superior energy efficiency and maneuverability through system-level integration of heterogeneous propulsion systems. As shown in Figure 7(f), Lu et al. (2021), Lu et al. (2022), Lyu et al. (2022), Hu et al. (2022), Bi et al. (2022b) developed a multimodal HAUV named Nezha III, capable of executing horizontal flight, vertical flight, hovering, and underwater gliding. To optimize payload capacity and underwater weight distribution, the team introduced a novel pneumatic buoyancy system, replacing traditional linear actuators for pitch control. Additionally, the vehicle incorporates foldable motor arms, enhancing hydrodynamic efficiency during aquatic opera-

tions through reduced drag and improved maneuverability. As shown in Figure 7(g), Bi et al. (2022a, 2023) developed a low-cost hybrid aerial underwater vehicle (HAUV), named Nezha-Mini, with a compact design weighing 953 grams and dimensions comparable to an A4 sheet. By integrating the structural configurations of a quadrotor unmanned aerial vehicle (UAV) and a 3-degree-of-freedom (3-DoF) UUV, the vehicle achieves full multi-domain mobility, operating at altitudes up to 50 meters and depths up to 6 meters. This design ensures rapid and stable cross-domain transitions, meeting the requirements for agile and efficient transmedium operations. As shown in Figure 7(f), Bai et al. (2023) developed a foldable and self-deployable HAUV, named Nezha-F, featuring a novel arm mechanism integrated with a piston-driven variable buoyancy system (PVBS). This compact design optimizes the trade-off between aerial and underwater performance by minimizing additional actuators, offering a scalable solution for the miniaturization of amphibious platforms. The foldable and self-deployable architecture enhances operational versatility while maintaining structural efficiency, demonstrating a significant advancement in lightweight HAAVs design. As shown in Figure 7(i), Jin et al. (2023) from developed a HAUV, named Nezha-IV, equipped with four aerial propellers and eight underwater thrusters. This configuration enables precise maneuverability in both aerial and aquatic environments, as well as robust dynamic transitions under challenging sea conditions. Nezha-IV demonstrates versatile operational capabilities, including underwater navigation at depths of 0–50 m with a sustained speed of 1 kn for 22 min, aerial hovering for 15 min, and aerial cruising at 10 m/s with a range of 7.2 km. As shown in Figure 7(j), Bi et al. (2024) designed a bone-shaped HAUV, named Nezha-B, featuring a double-layered and staggered quadrotor configuration that minimizes vehicle width. The streamlined hull design, combined with lightweight marine thrusters, enables an underwater speed of 1.67 m/s. This innovative architecture integrates the rapid maneuverability of a slender underwater vehicle with the inherent stability of a quadrotor, eliminating the need for complex morphing mechanisms while maintaining high performance in both aerial and aquatic domains. As shown in Figure 7(k), Jin et al. (2024) developed a tail-sitting fixed-wing vertical takeoff and landing (VTOL) HAUV, named Nezha-SeaDart. This vehicle is capable of VTOL from both terrestrial and aquatic surfaces, utilizing wing-generated lift for efficient aerial cruising and seamless water-air transitions. Nezha-SeaDart operates in a multi-phase mission profile: initiating vertical takeoff in quadcopter mode, transitioning to fixed-wing flight for aerial navigation, diving for underwater operations upon reaching the target area, and executing a vertical landing after water egress. This integrated operational capability enables Nezha-SeaDart to function as a versatile platform for multi-domain missions. As shown in Figure 7(l), Wang et al. (2024c) designed a multimodal tilt-rotor unmanned aerial-aquatic vehicle named Diving Hawk. The Diving Hawk can repeatedly cross domains and switch among four multi-domain motion modes as required. In the air, two tilt rotors and a fixed rotor are responsible for vertical takeoff and landing as well as multirotor flight, and the wings provide lift for fixed-wing flight. Underwater, the two tilt rotors perform vector propulsion, and underwater gliding is achieved through a movable buoyant tailplane and a distributed variable buoyancy system.

5 Analysis of HAAV design paradigms

Bio-inspired HAAVs derive their fundamental advantage from innovative locomotion mechanisms and biologically rational cross-medium transitions. This category encompasses three representative approaches: Flapping-wing propulsion employs periodic wing-like motions to generate biomimetic thrust, achieving high biomimetic fidelity during cross-medium transitions but often exhibiting limited thrust-to-power conversion efficiency and inadequate sustained aerial lift capability, resulting in constrained operational endurance and low payload capacity. Water-jet propulsion utilizes high-pressure fluid or chemically-driven jets to produce high instantaneous thrust, excelling in rapid water-to-air transition. However, constrained by propellant mass limitations and transient energy release characteristics, its continuous thrust capability and overall endurance are restricted. Morphing-structure designs do not directly generate propulsion but instead employ adaptive configurations such as foldable wings or bistable airfoils to significantly enhance hydrodynamic and aerodynamic performance during cross-medium transitions, thereby indirectly improving overall system efficiency. The endurance and payload of such platforms can reach moderate levels, heavily dependent on the integration of propulsion and energy subsystems, representing a critical pathway toward translating bio-inspired principles into practical engineering applications.

In contrast, drone-UUV integrated HAAVs place greater emphasis on systems engineering and multi-mission adaptability. Unimodal multi-rotor configurations employ a single set of propellers to operate in different media, leading to a significant efficiency trade-off in different fluids with vastly different densities and viscosities. Unimodal fixed-wing designs exhibit high aerodynamic efficiency and extended operational endurance potential in air, with their larger platform scale supporting higher payloads. Nevertheless, the use of common propulsion mechanisms for both underwater and aerial operation leads to a reduction in thruster efficiency, consequently impairing underwater maneuverability. Multimodal HAAVs incorporate medium-

specific thrust units or reconfigurable thrust-vectoring mechanisms to approach medium-specific efficiency optima. Although such HAAVs systems introduce greater structural and control complexity, they enable extended total cross-medium mission duration and higher payload capacity, thereby accommodating complex multi-phase operational profiles.

In summary, the two technical paradigms exhibit clear design trade-offs and evolutionary progression: Bio-inspired HAAVs demonstrate strong potential in locomotion-mechanism innovation and low-disturbance cross-medium transitio, but the pathway to practical deployment remains constrained by fundamental bottlenecks in power system scaling, energy density, and structural load-bearing capacity. Drone-UUV integrated platforms, leveraging relatively mature subsystems, offer distinct advantages in mission adaptability, system reliability, and payload capability, with the primary challenge lying in the modeling and coordinated control of cross-medium dynamic coupling. Looking ahead, the advancement of HAAVs from laboratory prototypes to field-ready systems hinges on the deep integration of both paradigms. This entails translating the efficient and robust cross-medium bio-inspired motion mechanisms into modular functional units. These units can then be integrated within future-generation HAAV platforms to achieve synergistic breakthroughs in locomotion performance, mission endurance, and engineering practicality.

6 Research challenges

The development of HAAVs faces critical barriers in achieving seamless cross-domain operations. This section outlines distinctly important challenges in three core areas: dynamic control during medium transitions, energy efficiency for extended endurance, and adaptive heterogeneous propulsion systems for discrepant environments.

6.1 Dynamic control in cross-media transitions

Cross-medium transitions involve strongly nonlinear and time-varying dynamics, posing severe challenges to conventional control methods.

6.1.1 Modeling challenges and nonlinear dynamics

Accurate modeling of transient forces at the air-water interface (e. g., attached water mass during water exit, slamming loads during water entry) is a prerequisite for precise control. High-fidelity numerical simulation and experimental system identification are key to constructing reduced-order models suitable for real-time control.

6.1.2 Advanced control strategies for transition phases

Traditional linear control or gain-scheduling methods lack sufficient adaptability when dealing with environmental disturbances such as waves and currents. Model predictive control (MPC) shows potential in managing thrust saturation and abrupt attitude changes during transitions due to its ability to handle constraints and predict system behavior. Disturbance-observer-based robust control methods can estimate and compensate for unmodeled hydrodynamic and aerodynamic disturbances online, enhancing system stability in complex environments.

6.1.3 Adaptive propulsion systems for multi-media

Designing a propulsion system that maintains high efficiency in both air and water without introducing excessive complexity and weight is a fundamental challenge in this field. Current main technical approaches include: employing tiltable or thrust-vectoring mechanisms to allow the same propeller to adapt to different media by changing its operating angle and rotational speed; or directly integrating two independent sets of propulsors, each optimized for air or water. Bio-inspired soft morphing structures and smart material-based actuators (e.g., dielectric elastomers, shape memory alloys) offer new methods for developing lightweight, efficient, and low-noise propulsio. These structures enable continuous, compliant shape changes to optimize flow fields in different media. However, their output force, response speed, and long-term reliability still require significant improvement. The performance of the propulsion system is tightly coupled with the vehicle's overall configuration, structural weight, and control strategy. Future design requires a multidisciplinary design optimization approach, jointly optimizing propeller parameters, airframe geometry, material selection, and control systems within a unified framework to seek globally optimal cross-medium performance, rather than a simple sum of individual subsystem performances. To address model uncertainties and highly time-varying environments, data-driven intelligent control methods are emerging as a key research direction. Reinforcement learning can be used to autonomously optimize cross-medium motion trajectories in simulation environments, while learning algorithms such as neural networks can train controllers to adapt to complex disturbances. Further, constructing “digital twin” systems capable of real-time sensor data fusion can provide HAAVs with persistent environmental awareness and adaptive decision-making capabilities.

6.2 Energy management for sustained operations

Dual-medium operations impose contradictory requirements on the energy density, power output, and management strategies of energy systems, constituting a core bottleneck limiting mission endurance.

6.2.1 Hybrid energy system architectures

Single battery systems struggle to meet the demands of long-endurance, high-power missions. The trend is toward building hybrid energy systems. For instance, high-energy-

density aqueous-reactive chemical fuels or fuel cells can handle high-power-demand phases like takeoff and transition, while lithium batteries power cruise and avionics. Additionally, exploring energy regeneration technologies, such as recovering kinetic energy during gliding or utilizing solar power in aerial phases, represents an important supplementary path to extending mission duration.

6.2.2 Intelligent energy allocation strategies

Different phases of a cross-medium mission have significantly divergent energy requirements. Therefore, intelligent energy management strategies are needed to dynamically optimize power allocation among the propulsion system, mission payload, and control system based on the current mission phase (e.g., underwater cruising, water-exit acceleration, aerial flight), environmental conditions, and remaining energy.

6.2.3 Reliability in extreme operating environments

Extreme operating environments, such as deep-sea high pressure and alternating high-low temperatures, pose challenges to the safety and reliability of energy systems. This necessitates the development of pressure-tolerant battery packaging, efficient thermal management systems.

6.3 Adaptive propulsion systems for multi-media

Designing a propulsion system that maintains high efficiency in both air and water without introducing excessive complexity and weight is a fundamental challenge in this field.

6.3.1 Dual-media propulsion design approaches

Current main technical approaches include: employing tiltable or thrust-vectoring mechanisms to allow the same propeller to adapt to different media by changing its operating angle and rotational speed; or directly integrating two independent sets of propulsors, each optimized for air or water.

6.3.2 Smart materials and morphing structures

Bio-inspired soft morphing structures and smart material-based actuators (e.g., dielectric elastomers, shape memory alloys) offer new methods for developing lightweight, efficient, and low-noise propulsion. These structures enable continuous, compliant shape changes to optimize flow fields in different media. However, their output force, response speed, and long-term reliability still require significant improvement.

6.3.3 Integrated system optimization framework

The performance of the propulsion system is tightly coupled with the vehicle's overall configuration, structural weight, and control strategy. Future design requires a multidisciplinary design optimization approach, jointly optimizing propeller parameters, airframe geometry, material selection, and control systems within a unified framework to seek globally optimal cross-medium performance, rather than a simple sum of individual subsystem performances.

6.4 Mission-oriented design consideration

The practical deployment of HAAVs necessitates a mission-driven design philosophy, where architectural design are fundamentally guided by specific operational requirements. In the context of deep-sea scientific exploration, missions rely on HAAVs with extended underwater endurance and substantial payload capacity—criteria that strongly favor large-scale, multimodal drone-UUV integrated systems. Such platforms usually combine the fixed-wing flight mode with underwater propulsion or gliding mode, which can meet the requirements for long-term marine research. Conversely, coastal monitoring and emergency response missions prioritize rapid deployment and adaptability to dynamic littoral environments. For example, unimodal multi-rotor systems are particularly well-suited for tasks that require vertical take-off and landing, precise hovering, and close-range manipulation, such as infrastructure inspection or targeted sampling. For broader-area surveillance, such as tracking pollution plumes or conducting coastal patrols, fixed-wing unimodal or hybrid multimodal designs with greater aerial endurance become advantageous. Notably, the low acoustic signature and biomimetic mobility of certain bio-inspired platforms also present unique benefits for ecological monitoring missions where minimal disturbance is paramount. Therefore, the design of HAAV is not determined by a single optimal design direction, but is customized for specific task parameters. Deep-sea exploration prioritizes endurance and payload, favoring multimodal systems, while coastal operations emphasize adaptability and rapid response, employing a range of agile platforms. This task-oriented HAAV design provides a clear direction for the future development of the HAAV platform.

7 Conclusion

HAAVs represent a transformative frontier in robotics, merging bio-inspired principles with advanced engineering to achieve seamless air-water transitions. This review systematically categorizes HAAV development into two paradigms: biomimetic mechanisms and drone-UUV integrated systems. Biomimetic designs, such as flapping-wing and water-jet propulsion, emulate organisms like flying fish and squids to optimize efficiency and adaptability. Innovations like bistable airfoils and morphing structures further enhance dynamic reconfiguration for multi-domain performance. Meanwhile, drone-UUV integration leverages modular architectures, hybrid thrust mapping, and active buoyancy control to balance operational simplicity

and functional versatility.

Key challenges persist in cross-medium dynamic coupling, where nonlinear hydrodynamic-aerodynamic interactions complicate control frameworks, and energy efficiency, as divergent power demands strain dual-domain operations. Additionally, reliable communication across air-water interfaces remains hindered by signal attenuation. Addressing these issues necessitates interdisciplinary collaboration across biomechanics, fluid dynamics, and embedded systems.

Future research should prioritize adaptive control algorithms for transient phases, energy-dense power systems tailored for multi-domain missions, and novel communication protocols to ensure robustness in dynamic environments.

Funding Supported in part by the National Natural Science Foundation of China under Grant Nos. 51939003 and 52301364, Shandong Provincial Natural Science Foundation under Grant No. ZR2023QE027.

Competing interests Hongde Qin is an editorial board member for the Journal of Marine Science and Application and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

References

Alzu'bi H, Mansour I, Rawashdeh O (2018) Loon Copter: Implementation of a hybrid unmanned aquatic–aerial quadcopter with active buoyancy control. Journal of Field Robotics 35(5): 764-778. https://doi.org/10.1002/rob.21777

Bai YL, Jin YF, Liu CH, Zeng Z, Lian L (2023) Nezha-F: Design and analysis of a foldable and self-deployable HAUV. IEEE Robotics and Automation Letters 8(4): 2309-2316. https://doi.org/10.1109/LRA.2023.3252343

Bao JQ, Mu XK, Xue YF, Zhu ZB, Qin HD (2025) Robust multi-sensor fusion for unmanned underwater vehicle navigation. Measurement 253(A): 117450. https://doi.org/10.1016/j.measurement.2025.117450

Bi YB, Jin YF, Lyu CX, Zeng Z, Lian L (2022a) Nezha-Mini: Design and locomotion of a miniature low-cost hybrid aerial underwater vehicle. IEEE Robotics and Automation Letters 7(3): 6669-6676. https://doi.org/10.1109/LRA.2022.3176438

Bi YB, Jin YF, Zhou HX, Bai YL, Lyu CX, Zeng Z (2023) Surfing Algorithm: Agile and safe transition strategy for hybrid aerial underwater vehicle in waves. IEEE Transactions on Robotics 39(6): 4262-4278. https://doi.org/10.1109/TRO.2023.3319928

Bi YB, Lu D, Zeng Z, Lian L (2022b) Dynamics and control of hybrid aerial underwater vehicle subject to disturbances. Ocean Engineering 250: 110933. https://doi.org/10.1016/j.oceaneng.2022.110933

Bi YB, Xu ZX, Shen YS, Zeng Z, Lian L (2024) Design and implementation of a bone-shaped hybrid aerial underwater vehicle. IEEE Robotics and Automation Letters 9(8): 7318-7325. https://doi.org/10.1109/LRA.2024.3420550

Chen Y, Wang H, Helbling EF, Jafferis NT, Zufferey, R, Ong A, Ma K, Gravish N, Chirarattananon P, Kovac M,Wood RJ (2017) A iologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. Science Robotics 2(11): eaao5619. https://doi.org/10.1126/scirobotics.aao5619

DJI Inspire 3 (2025) DJI Inspice 3. Available from https://www.dji.com/inspire-3?backup_page=index [Accessed on Apr. 22, 2025]

Dong YX, Liang JH, Yang XB, Huang JG, Xue XQ, Fan YB (2017) Modeling and simulation of cormorant's webbed-feet assisted take-off from water surface. 2017 IEEE International Conference on Robotics and Biomimetics, Macau, China, 1659-1664. https://doi.org/10.1109/ROBIO.2017.8324656

Edwards D, Arnold N, Heinzen S, Strem C, Young T (2017) Flying emplacement of an underwater glider. OCEANS 2017-Anchorage, Anchorage, USA, 1-6

Gao A, Techet AH (2011) Design considerations for a robotic flying fish. OCEANS'11 MTS/IEEE KONA, Hawaii, USA, 1-8. https://doi.org/10.23919/OCEANS.2011.6107039

Gu L, Xiang Y, Gong ZY, Tao B (2024) Bio-inspired wing with bistable morphing airfoils for aquatic-aerial robots. IEEE Robotics and Automation Letters 9(7): 6704-6711. https://doi.org/10.1109/LRA.2024.3408077

Han ZL, Cao J, Li Y, Li HW, Du ZP, Fu JY, Wan L (2024) Experimental study on the hydrodynamic of foldable-wing unmanned aerial-underwater vehicles during water-exit process. Ocean Engineering 310: 118600. https://doi.org/10.1016/j.oceaneng.2024.118600

Hou TG, Yang XB, Su HH, Chen LK, Wang TM, Liang JH (2019a) Design, fabrication and morphing mechanism of soft fins and arms of a squid-like aquatic-aerial vehicle with morphology tradeoff. 2019 IEEE International Conference on Robotics and Biomimetics, Dali, China, 1020-1026. https://doi.org/10.1109/ROBIO49542.2019.8961447

Hou TG, Yang XB, Su HH, Jiang BH, Chen LK, Wang TM (2019b) Design and experiments of a squid-like aquatic-aerial vehicle with soft morphing fins and arms. 2019 International Conference on Robotics and Automation, Montreal, Canada, 4681-4687. https://doi.org/10.1109/ICRA.2019.8793702

Hou TG, Yang XB, Wang TM, Liang JH, Li SW, Fan YB (2020) Locomotor transition: how squid jet from water to air. Bioinspiration & Biomimetics 15(3): 036014. https://doi.org/10.1088/1748-3190/ab784b

Hu R, Lu D, Xiong CK, Lyu CX, Zhou HX, Jin YF, Wei TJ, Yu CY, Zeng Z, Lian L (2022) Modeling, characterization and control of a piston-driven buoyancy system for a hybrid aerial underwater vehicle. Applied Ocean Research 120: 102925. https://doi.org/10.1016/j.apor.2021.102925

Huang DY, Dou MH, Liu XC, Wang XY, Wang CG, Chen BM (2024a) Aqua slide: An underwater leveling motion scheme for M-UAAV utilizing singularity. IEEE Transactions on Industrial Electronics 72(6): 6233-6243. https://doi.org/10.1109/TIE.2024.3497339

Huang DY, Dou MH, Liu XC, Yan RX, Gao SQ, Liu ZX (2024b) First principle modeling of a morphable unmanned aerial-aquatic vehicle: Mirs-Alioth. 2024 IEEE 18th International Conference on Control & Automation, Reykjavík, Iceland, 540-545. https://doi.org/10.1109/ICCA62789.2024.10591869

Jin YF, Bi YB, Lyu CX, Bi YB, Lian L (2023) Nezha-IV: A hybrid aerial underwater vehicle in real ocean environments. Journal of Field Robotics 41(2): 420-442. https://doi.org/10.1002/rob.22274

Jin YF, Zen Z, Lian L (2024) Nezha-SeaDart: A tail-sitting fixed-wing vertical takeoff and landing hybrid aerial underwater vehicle. Journal of Field Robotics 42(1): 137-152. https://doi.org/10.1002/rob.22399

Li L, Liu WB, Tian BC, et al. (2023) An aerial–aquatic hitchhiking robot with remora-inspired tactile sensors and thrust vectoring units. Advanced Intelligent Systems 2023: 2300381. https://doi.

org/10.1002/aisy.202300381

Liang JH, Yao GC, Wang TM, Yang XB, Zhao WD, Song G, Zhang YC (2013) Wing load investigation of the plunge-diving locomotion of a gannet Morus inspired submersible aircraft. Science China Technological Sciences 57: 390-402. https://doi.org/10.1007/s11431-013-5437-5

Liu X, Dou M, Huang D, Gao SQ, Yan RX, Wang B (2023) TJ-FlyingFish: Design and implementation of an aerial-aquatic quadrotor with tiltable propulsion units. 2023 IEEE International Conference on Robotics and Automation, London, UK, 7324-7330. https://doi.org/10.1109/ICRA48891.2023.10160899

Lu D, Guo YH, Xiong CK, Zeng Z, Lian L (2022) Takeoff and landing control of a hybrid aerial underwater vehicle on disturbed water's surface. IEEE Journal of Oceanic Engineering 47(2): 295-311. https://doi.org/10.1109/JOE.2021.3124515

Lu D, Xiong CK, Lyu BZ, Zeng Z, Lian L (2018) Multi-mode hybrid aerial underwater vehicle with extended endurance. 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans, Kobe, Japan, 1-7. https://doi.org/10.1109/OCEANSKOBE.2018.8559438

Lu D, Xiong CK, Zhou HX, Lyu CX, Hu R, Yu CY, Zeng Z, Lian L (2021) Design, fabrication, and characterization of a multimodal hybrid aerial underwater vehicle. Ocean Engineering 219: 108324. https://doi.org/10.1016/j.oceaneng.2020.108324

Lu D, Xiong CK, Zeng Z, Lian L (2019) A multimodal aerial underwater vehicle with extended endurance and capabilities. 2019 International Conference on Robotics and Automation, Montreal, Canada, 4674-4680. https://doi.org/10.1109/ICRA.2019.8793985

Lyu CX, Lu D, Ciong CK, Lyu C, Lu D, Xiong C, Hu R, Jin Y, Wang J, Zeng Z, Lian L (2022) Toward a gliding hybrid aerial underwater vehicle: Design, fabrication, and experiments. Journal of Field Robotics 39(5): 543-556. https://doi.org/10.1002/rob.22063

Maia MM, Mercado DA, Diez FJ (2017) Design and implementation of multirotor aerial-underwater vehicles with experimental results. 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vancouver, Canada, 961-966. https://doi.org/10.1109/IROS.2017.8202261

Moore J, Fein A, Setzler W (2018) Design and analysis of a fixed-wing unmanned aerial-aquatic vehicle. 2018 IEEE International Conference on Robotics and Automation, Brisbane, Australia, 1236-1243. https://doi.org/10.1109/ICRA.2018.8461240

Nguyen K, Park HC (2023) Feasibility study on mimicking the tail-beating supported gliding flight of flying fish. Ocean Engineering 287: 115745. https://doi.org/10.1016/j.oceaneng.2023.115745

Pham TH, Nguyen K, Park HC (2023) A robotic fish capable of fast underwater swimming and water leaping with high Froude number. Ocean Engineering 268: 113512. https://doi.org/10.1016/j.oceaneng.2022.113512

Ravell DAM, Maia MM, Diez FJ (2018) Modeling and control of unmanned aerial/underwater vehicles using hybrid control. Control Engineering Practice 76: 112-122. https://doi.org/10.1016/j.conengprac.2018.04.006

Reid BD (2012) The flying submarine: The story of the invention of the Reid Flying Submarine, RFS-1. Heritage Books

Rockenbauer FM, Jeger S, Beltran L, Berger MA, Harms M, Kaufmann N, Rauch M, Reinders M, Lawrance N, Stastny T, Siegwart RY (2021) Dipper: A dynamically transitioning aerial-aquatic unmanned vehicle. Robotics: Science and Systems 2021, 12-16. https://doi.org/10.15607/RSS.2021.XVII.048

Saildrone Surveyor (2025) Saildrone Surveyor. Available from https://www.saildrone.com/solutions/ocean-survey [Accessed on Apr. 22, 2025]

Siddall R, Kovac M (2017) Fast aquatic escape with a jet thruster. IEEE/ASME Transactions on Mechatronics 22(1): 217-226. https://doi.org/10.1109/TMECH.2016.2623278

Siddall R, Ortega A, Kovač M (2017) Wind and water tunnel testing of a morphing aquatic micro air vehicle. Interface Focus 7: 20160085. http://doi.org/10.1098/rsfs.2016.0085

Stewart W, Weisler W, Anderson M, Bryant M, Peters K (2020) Dynamic modeling of passively draining structures for aerial–aquatic unmanned vehicles. IEEE Journal of Oceanic Engineering 45(3): 840-850. https://doi.org/10.1109/JOE.2019.2898069

Stewart W, Weisler W, MacLeod M, Powers T, Defreitas A, Gritter R, Anderson M, Peters K, Gopalarathnam A, Bryant M (2018) Design and demonstration of a seabird-inspired fixed-wing hybrid UAV-UUV system. Bioinspiration & Biomimetics 13(5): 056013. https://doi.org/10.1088/1748-3190/aad48b

Sun XR, Cao J, Li Y, Ling Y (2024) Efficient prediction method for the water-exit characteristics of unmanned aerial-underwater vehicles. Ocean Engineering 302: 117403. https://doi.org/10.1016/j.oceaneng.2024.117403

Sun XR, Cao J, Li Y, Wang BX (2023) Design and field test of a foldable wing unmanned aerial–underwater vehicle. Journal of Field Robotics 41(2): 347-373. https://doi.org/10.1002/rob.22265

Tan YH, Chen BM (2019) Design of a morphable multirotor aerial-aquatic vehicle. OCEANS 2019 MTS/IEEE SEATTLE, Seattle, USA, 1-8

Tan YH, Chen BM (2020) A morphable aerial-aquatic quadrotor with coupled symmetric thrust vectoring. 2020 IEEE International Conference on Robotics and Automation, Paris, France, 2223-2229. https://doi.org/10.1109/ICRA40945.2020.9196687

Tan LG, Liang S, Su HX, Qin Z, Li L, Huo J (2023) Research on amphibious multi-rotor UAV out-of-water control based on ADRC. Applied Sciences 13(8): 4900. https://doi.org/10.3390/app13084900

TWIN-TAILED SCORPION (2017) TWIN-TAILED SCORPION. Available from https://www.tengden.com/product/6.html [Accessed on Apr. 22, 2025]

Villegas A, Mishkevich V, Gulak Y, Diez FJ (2017) Analysis of key elements to evaluate the performance of a multirotor unmanned aerial–aquatic vehicle. Aerospace Science and Technology 70: 412-418. https://doi.org/10.1016/j.ast.2017.07.046

Wang TM, Yang XB, Liang JH, Yao GC, Zhao WD (2013) CFD based investigation on the impact acceleration when a gannet impacts with water during plunge diving. Bioinspiration & Biomimetics 8(3): 036006. https://doi.org/10.1088/1748-3182/8/3/036006

Wang XY, Pei X, Wu JH, Wang XX, Hou TG (2023) Design, fabrication and fine-tuning of an aerial-aquatic explosive water-jet thruster with repeatable propulsion capability. 2023 IEEE International Conference on Robotics and Biomimetics, Koh Samui, Thailand, 1-6. https://doi.org/10.1109/ROBIO58561.2023.10354615

Wang XY, Pei X, Zhu RX, Hou TG, Yang XB (2024a) Cavity-membrane-based water-jet bio-inspired thruster with multidirectional accelerating capability. IEEE/ASME Transactions on Mechatronics 29(5): 3312-3323. https://doi.org/10.1109/TMECH.2023.3340885

Wang XY, Zhao JW, Pei X, Wang TM, Hou TG, Yang XB (2024b) Bioinspiration review of aquatic unmanned aerial vehicle (AquaUAV). Biomimetic Intelligence and Robotics 4(2): 100154. https://doi.org/10.1016/j.birob.2024.100154

Wang ZJ, Jiang YH, Zou ZH, Zhen ZK (2024c) Design and

implementation of a multimodal tilt-rotor unmanned aerial-aquatic vehicle. Journal of Field Robotics 2024: 1-17. https://doi.org/10.1002/rob.22478

Wei TJ, Hu R, Li JP, Bi YB, Jin YF, Lu D, Zeng Z, Lian L (2022a) Experimental study on trans-media hydrodynamics of a cylindrical hybrid unmanned aerial underwater vehicle. Ocean Engineering 252: 111190. https://doi.org/10.1016/j.oceaneng.2022.111190

Wei TJ, Lu D, Zeng Z, Lian L (2022b) Trans-media kinematic stability analysis for hybrid unmanned aerial underwater vehicle. Journal of Marine Science and Engineering 10(2): 275. https://doi.org/10.3390/jmse10020275

Wei TJ, Zhou ZY, Wang YD, Zeng Z, Lian L (2023) Hydrodynamic study of hybrid aerial underwater vehicle in the wind, wave, and current environment. 2023 IEEE Underwater Technology, Tokyo, Japan, 1-6. https://doi.org/10.1109/UT49729.2023.10103380

Weisler W, Stewart W, Anderson MB, Peters KJ, Gopalarathnam A, Bryant M (2018) Testing and characterization of a fixed wing cross-domain unmanned vehicle operating in aerial and underwater environments. IEEE Journal of Oceanic Engineering 43(4): 969-982. https://doi.org/10.1109/JOE.2017.2742798

Yao GC, Liang JH, Wang TM, Yang XB, Liu M, Zhang YC (2014) Submersible unmanned flying boat: Design and experiment. 2014 IEEE International Conference on Robotics and Biomimetics, Bali, Indonesia, 1308-1313. https://doi.org/10.1109/ROBIO.2014.7090514

Young TZ (2014) Design and testing of an unmanned aerial to underwater vehicle. 14th AIAA Aviation Technology, Integration, and Operations Conference, Atlanta, USA, 1-15

Zha J, Thacher E, Kroeger J, Mäkiharju SA, Mueller MW (2019) Towards breaching a still water surface with a miniature unmanned aerial underwater vehicle. 2019 International Conference on Unmanned Aircraft Systems, Atlanta, USA, 1178-1185. https://doi.org/10.1109/ICUAS.2019.8798350

Zufferey R, Ancel A, Farinha A, Siddall R (2019) Consecutive aquatic jump-gliding with water-reactive fuel. Science Robotics 4(34): eaax7330. https://doi.org/10.1126/scirobotics.aax7330