Cross-Medium Vehicle Design

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Abstract. Cross-medium vehicles are defined as “new-concept amphibious unmanned platforms capable of freely traversing between water and air.” With societal development in the 21st century, the aerial flight capabilities and underwater navigation capabilities of cross-medium vehicles have greatly met the demand for activities in both water and air. Their excellent mobility and concealment provide broad application prospects in both civilian and military fields. This paper analyzes the current development status of cross-medium vehicles domestically and internationally, focusing on three major design schemes: the water-entry performance and underwater navigation capability of swept-wing models, the stability and response speed of medium transitions in multi-rotor models, and the autonomous movement and cross-medium motion stability of hybrid-wing models. Additionally, two driving schemes are discussed: independent water-air propulsion and integrated water-air propulsion. The research highlights, challenges, and core technologies required for cross-medium vehicles are summarized.

Keywords: Cross-medium vehicles, Shape design, Propulsion, Simulation analysis

1 Introduction

Cross-medium vehicles are defined as “new-concept amphibious unmanned platforms capable of freely traversing between water and air.” Since the concept of cross-medium vehicles was first implemented in the 1930s, countries such as France, the United Kingdom, the United States, Russia, and China have conducted principle designs and test flights of various types of cross-medium vehicles over the following decades. Although preliminary results have been achieved, the technology for “repeated water-air medium transitions” has not yet been fully realized.

In the 21st century, the aerial flight capabilities and underwater navigation abilities of cross-medium vehicles have significantly met the growing demand for activities across water and air. With excellent mobility and concealment, these vehicles offer broad application prospects in both civilian and military fields. Research on the design and improvement of cross-medium vehicles also contributes to the advancement of related disciplines, such as energy dynamics, fluid mechanics, mechanical structure design, communication and navigation control, and bionics.

This paper analyzes and summarizes the development status and research methodologies of existing cross-medium vehicles both domestically and internationally,

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identifying the research hotspots, challenges, and core technologies required in the field. It aims to provide readers with a comprehensive, in-depth, and inspiring perspective to further promote research and development in the field of cross-medium vehicles.

2 Development of Cross-Medium Vehicles

The concept of "dual-use for water and air" in cross-medium vehicles initially appeared in science fiction literature. In the 1930s, the Soviet Union first proposed a "new weapon concept" that combined the airplane, an "air-based weapon," with the submarine, a "strategic underwater weapon," to realize a dual-use water-air platform. This led to the successful design of the LPL—"flying submarine" prototype, marking the practical initiation of cross-medium vehicle design and improvement. Subsequently, the Soviet Union developed three representative conceptual prototypes: the RFS-1, Convair, and DARPA models. However, due to technological limitations at the time, none of these prototypes succeeded in practical applications that could achieve water-air medium transitions [1].

In the 21st century, with societal advancements, human demand for activities across water and air has increased significantly. A series of attempts and improvements have been made in the design and development of cross-medium vehicle prototypes in Europe, the United States, and China.

In Europe, the Aelius prototype, developed by Bordeaux Aviation Technology in France, underwent water testing in 2007 [2]. In 2008, the British company Warrior Sea-Air Technology successfully tested the GULL 36, part of the Seagull series of unmanned waterborne drones using a pontoon structure [3]. In 2016, Imperial College London employed bioinspired technology to design the AquaMAV (Aquatic Micro Air Vehicle), an amphibious vehicle modeled after the morphology of the gannet bird [3].

Fig. 1. The Seagull series unmanned waterborne drone GULL 36

In the United States, research on cross-medium vehicles dates back to 1996, with the "Sea Seeker" developed by Northrop Grumman under commission from the U.S. Navy [3]. In 2005, Lockheed Martin was commissioned by the U.S. Defense Advanced Research Projects Agency (DARPA) to develop the Cormorant UAV (Unmanned

Aerial Vehicle), which incorporated bioinspired technology to mimic the water entry and exit behaviors of cormorants in its design and principles [2].

Fig. 2. Cormorant UAV

The first waterborne UAV utilizing lidar sensors for autonomous navigation was successfully developed in 2006 by an Oregon steelworks company [3]. In December 2013, the U.S. Navy announced the successful completion of verification tests for the Sea-Robin XFC submarine-launched UAV [3]. In 2016, the Blackwing submarine-launched UAV was deployed for intelligence gathering, reconnaissance, and relay communication tasks. In 2017, Hamzeh Alzu'bi et al. introduced the Loon Copter, a quadcopter prototype with active buoyancy control [3]. In February 2018, North Carolina State University, in collaboration with Triton Science and Imaging, developed the Eagle Ray, a fixed-wing trans-medium aircraft [4].

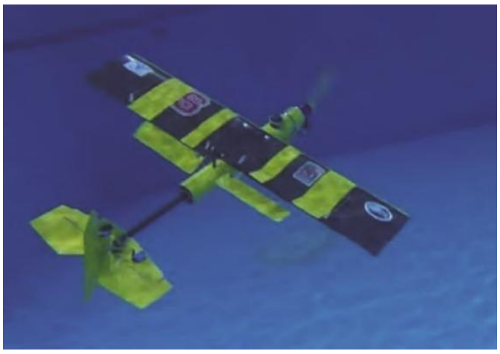

Fig. 3. The Eagle Ray fixed-wing trans-medium aircraft

In China, significant progress has also been made. In 2009, Beihang University developed an amphibious vehicle prototype using bioinspired design based on the morphology of flying fish, incorporating variable-sweep wings for buoyancy adjustment to transition between water and air. In 2015, the same research group developed another cross-medium unmanned vehicle inspired by the gannet bird [3].

In 2011, Nanchang Hangkong University developed two unmanned submarine prototypes powered by fully electric and hybrid oil-electric drives, featuring wings with a 90° variable sweep angle [3]. In 2019, Nanjing University of Aeronautics and

Astronautics designed and prototyped a bionic cross-medium vehicle inspired by the ringed pectoral fins of marine organisms [5]. In 2022, students from Shanghai Jiao Tong University completed the Nezha platform, the world's first sea-air integrated cross-domain vehicle. This platform boasts the greatest diving depth, highest load capacity, and widest underwater operating range among similar publicly disclosed projects worldwide [6].

Fig. 4. The "Nezha" sea-air integrated cross-domain vehicle platform developed by Shanghai Jiao Tong University

Currently, research and development of cross-medium vehicles have seen considerable maturity in waterborne UAVs and submarine-launched UAVs, with the United States leading in prototype technology. Europe has also developed a number of experimental prototypes, while China's existing prototypes are mainly the result of university-led independent research and development. Although European and Chinese prototypes are predominantly in the research stage, further development and improvement are needed to produce cross-medium vehicles that are ready for mass production and practical applications.

As a new concept proposed in recent decades, water-air trans-medium vehicles face stringent requirements to ensure stable operations in both mediums and to perform functions such as reconnaissance and transportation. These requirements necessitate advancements in deformation mechanisms, water-air propulsion systems, and guidance and control technologies. Consequently, further research in this field can drive progress in disciplines such as material fabrication, electronic circuit design, mechanical engineering, dynamics, and computational control. Compared to existing international research, domestic innovations in vehicle shape design, medium transition methods, and control mechanisms require further development to establish a more mature and systematic research and manufacturing framework.

3 Cross-Medium Aircraft Shape Design

Early water-air cross-medium aircraft primarily adopted three traditional structures: fixed wings, multi-rotors, and flapping wings. With increased research on cross-medium stability, the development of shape design has diversified, introducing swept wings, multi-rotors, combination wings, and bionic wings. This paper mainly compares swept wings, multi-rotors, and combination wings in terms of flight performance and water-entry buffering.

3.1 Swept Wings

The design inspiration for swept wings originates from the diving and prey-catching behavior of waterfowl such as gannets. Using bionic design methods, it references how waterfowl fold their wings and adjust the sweep angle to enable rapid water entry.

The concept of swept-wing design was first introduced in 2010 in New Scientist magazine. Submarine designer HAWKS proposed mimicking the diving behavior of waterfowl to address the issue of water entry for aircraft [7]. In 2012, Fabian et al. at the Massachusetts Institute of Technology designed the Bionic Gannet (MIT) experimental prototype and conducted water-entry experiments to verify the feasibility of swept-wing aircraft. When transitioning from air to water, the Bionic Gannet mimicked the gannet’s diving mode, striking the water at a speed of 7 m/s. It rapidly swept its wings back to reduce the impact load during water entry, preventing structural damage. After successful water entry, the Bionic Gannet adjusted its overall density to balance buoyancy and gravity, achieving a stable underwater motion state. Although this aircraft successfully demonstrated the feasibility of swept wings for diving into water, it was unable to cruise underwater or take off from water, falling short of the requirements for “repeated cross-medium transitions” [8].

In 2012, Liang Jianhong and his team at Beihang University developed a swept-wing aircraft called Gannet I (BUAA). Through water-entry testing, they examined overload conditions and wing root pivot tension under varying water-entry speeds, angles, and wing sweep angles. This provided reference data for the subsequent structural design, material strength selection, and underwater motion control algorithms of the improved Gannet II (BUAA) [8].

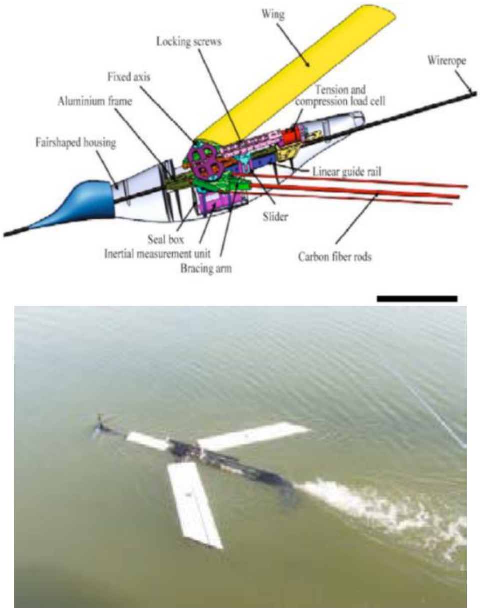

Fig. 5. Gannet I (BUAA) and Gannet II (BUAA) Diving Drones

In 2014, Liang's team introduced a large swept-wing underwater aircraft called Flying Fish [9], with a body length of 1.98 m, a wingspan of 3.4 m, a wing area of 1.5 m², a flight speed of 85 km/h, and a maximum altitude of 500 meters. It employed a hydraulic jet propulsion system but had a low underwater cruising speed of only 0.2–0.5 m/s, which fell far short of practical application requirements. Additionally, its large wing design made the overall body volume too large, limiting the prototype to low-efficiency gliding landings and takeoffs.

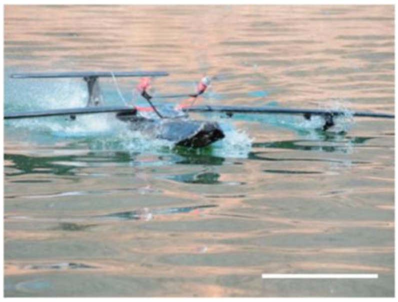

Fig. 6. Flying Fish Bionic Aircraft

In 2016, Siddall et al. at Imperial College London designed a swept-wing aircraft named AquaMAV (Aquatic Micro Air Vehicle) [3], inspired by gannets. The wing design consisted of three parts: the first part was attached to the main body, while the outer two parts were connected to the first via sealed bearings. During water-entry motion, the wings could sweep backward 90° to transition the aircraft passively from flight mode to dive mode, reducing the impact force on the body during water entry. Aerodynamic evaluations in wind tunnels and water tunnels confirmed AquaMAV's excellent flight performance with extended wings and low drag and lift with folded wings. Additionally, the team adjusted flight speed and altitude to modify water-entry parameters, successfully conducting multiple water-entry flight tests that demonstrated the buffering effect of the swept wings. Although its flight speed reached 18 m/s, AquaMAV's underwater propulsion and energy efficiency remain areas for improvement [8].

Fig. 7. AquaMAV (Aquatic Micro Air Vehicle)

In 2021, Friedrich et al. at ETH Zurich introduced a swept-wing aircraft called Dipper [8]. Its design resembled the Bionic Gannet (MIT) prototype by Fabian et al., with the addition of a T-tail structure. The main innovation lay in the propulsion system, which utilized reversible motors to independently drive aerial and aquatic propellers, reducing the propulsion system's weight. However, the low body density of this prototype meant that the diving motion alone could not fully submerge the body into water; additional propulsion from the propellers was required. The complex control mechanisms for Dipper's water-entry motion prevented it from achieving seamless transitions from diving landings to underwater cruising, limiting its operational flexibility.

3.2 Multirotor

The multirotor is the most widely used structure for unmanned aerial vehicles (UAVs), suitable for low-altitude, low-speed operations, vertical takeoff and landing, and hovering. By equipping a single aircraft with multiple aerial propellers, it can generate substantial lift and achieve a high thrust-to-weight ratio. Multirotor cross-medium vehicles can adjust their flight resistance and torque by controlling the rotor speed of their electric motors, enabling better maneuverability during water entry and exit, and ensuring stability and continuity during medium transitions.

In 2014, Drews et al. from the Federal University of Rio Grande do Sul [10] first demonstrated the feasibility of multirotor cross-medium vehicles. The prototype model was equipped with four aerial propellers for various operational scenarios and four aquatic propellers. A power evaluation test was conducted on the prototype in 2019. However, the dual independent propulsion systems for water and air significantly increased the vehicle's weight, severely reducing the performance of multirotor vehicles, which already suffer from limited range.

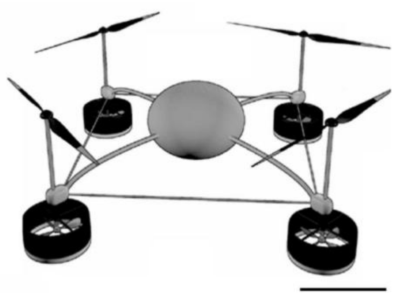

Fig. 8. Prototype model designed and developed by Drews et al. in 2014

Fig. 9. Prototype developed by Drews et al. in 2014

In 2015, Alzu'bi et al. from the University of Auckland [11] addressed the issue of excessive weight and developed a prototype called the Loon Copter. The Loon Copter required only four fixed-pitch aerial propellers to meet the propulsion needs for both underwater and aerial movement. To account for differences in water and air density, the team proposed a propulsion scheme compatible with both media based on variable-speed aerial propellers. By reducing the rotational speed of aerial propellers underwater, the system could accommodate underwater motion requirements. However, experiments showed that when propellers and parts of the fuselage were raised above the water surface, the propeller thrust significantly decreased. As a result, the propellers needed to rapidly increase their rotational speed to generate sufficient lift to prevent the fuselage from falling back into the water. This imposed extremely high demands on the responsiveness of the control system.

Fig. 10. Loon Copter prototype

In 2015, Maia et al. from Rutgers University, funded by the U.S. Navy, released the Naviator multirotor vehicle. The Naviator utilized a dual-layer coaxial octocopter structure to address the issue of sudden loss of lift during water exit. During water entry, the upper layer maintained rotation to stabilize the vehicle's motion; during water exit, the lower-layer rotors ensured balance after breaking the water surface. The Naviator's structural and dynamic strategies enabled smoother and faster medium transitions [8].

The work of Alzu'bi et al. and Maia et al. pioneered the application of integrated water-air propulsion technology in multirotor structures. Since then, various methods to enhance the motion performance of multirotor vehicles have been proposed.

In 2022, Li Li et al. from Beihang University [12] designed an adaptive propeller structure. The transformation of the propeller's form between water and air effectively shortened the time required for speed adjustments. Additionally, Li Li et al. proposed a low-energy-cost attachment scheme by studying adhesive structures. With the assistance of a biomimetic disk, the vehicle could adhere to the sidewalls of ships or the surfaces of marine organisms, facilitating activities such as carrying equipment and conducting underwater exploration.

Fig. 11. Prototype designed and developed by Li Li et al.

3.3 Combination Wing

The concept of combination wings originated in 2018 when Stewart et al. proposed three cross-medium vehicle design concepts inspired by the hunting behavior of seagulls: the quadrotor/fixed-wing hybrid vehicle, the VTOL (vertical take-off and landing) tail-sitter vehicle, and the water-jet take-off vehicle. The quadrotor/fixed-wing hybrid vehicle is also referred to as the combination wing vehicle [8].

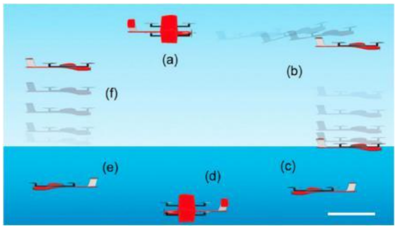

Fig. 12. Design concepts by Stewart et al.

In 2017, Lu Di et al. from Shanghai Jiao Tong University [13] initiated their combination wing vehicle project and released a series of Nezha vehicles. Among them, the second-generation Nezha was equipped with a pair of fixed wings, four rotors, and a lightweight pneumatic buoyancy (LPB) system. The fixed wings function as flight wings in the air and as glide wings underwater, while the rotors ensure stable take-off and landing. Additionally, the LPB system significantly enhances underwater cruising performance. The prototype can perform four primary actions: vertical take-off and landing, hovering, aerial flight, and underwater cruising. The thrust generated by the rotors counteracts the gravity of the vehicle during hovering, take-off, or landing, while in aerial flight, it overcomes air resistance and works in tandem with lift generated by the fixed wings to offset part of the gravity. During underwater cruising, the vehicle's motion is controlled by the LPB system installed at the front of the fuselage, which features external safety airbags. These airbags inflate or deflate using high-pressure gas, allowing the vehicle to achieve positive or negative buoyancy and enabling nose-up or nose-down movements. However, the underwater navigation capabilities of Nezha II still have room for optimization: the maximum diving depth is only 5 meters; its underwater motion control lacks precision, and it cannot autonomously change its diving direction; the motor arm structure significantly affects hydrodynamic performance, and its payload capacity is highly limited.

Fig. 13. Nezha II vehicle

In 2021, Lu Di et al. released an improved version of Nezha II, called Nezha III (Tail-sitter) [6], achieving significant improvements in diving depth, endurance, and motion autonomy. They replaced the traditional buoyancy control system used in underwater gliders (UGs) with a lightweight pneumatic buoyancy system, enabling a maximum diving depth of 50 meters. By conducting buoyancy-pitch coupling research, they proposed a horizontal gliding pitch control strategy that reduces energy consumption compared to the detachable internal mass method commonly used in underwater glider designs. They also designed foldable motor arms to address the issue of body overturning caused by changes in the center of gravity during take-off. The research team proposed a take-off and landing control method for Nezha III to counteract surface wave disturbances and enhance the stability of cross-medium motion, as well as a dynamic trajectory planning method for dual-medium motion in air and water.

To further improve underwater endurance, Lu Di et al. developed a piston-based variable buoyancy system in 2022 and released an improved prototype, Nezha III (VTOL) [8]. Water entry tests demonstrated that the maximum working depth of this prototype reached 35.5 meters, and it could perform underwater cruising activities continuously for 24 hours.

Fig. 14. Nezha III (Tail-sitter) vehicle

Fig. 15. Nezha III (VTOL) vehicle

4 Propulsion Systems for Cross-Medium Vehicles

Cross-medium vehicles are designed to operate in both aerial flight and underwater navigation. The significant differences in physical parameters between air and water present unique challenges: water's density is approximately 800 times that of air, and its viscosity coefficient is about 59 times higher than air. Consequently, the working principles and mechanisms of propulsion systems used in air and water differ significantly.

In aerial flight, the lift-to-drag ratio is a critical factor in evaluating the performance of propulsion systems, where the vehicle's weight is a key limiting factor. In underwater navigation, the drag primarily depends on the size and surface area of the vehicle, making size another critical constraint for cross-medium vehicles. Therefore, the energy source selection for cross-medium propulsion systems must account for both weight and size limitations.

Currently, propulsion systems for cross-medium vehicles can be categorized into two types: air-water independent systems and integrated air-water systems. Vehicles with air-water independent systems employ separate propulsion devices for aerial and underwater operations, with no interference or overlap in their energy or control systems. In contrast, vehicles with integrated air-water systems use a single propulsion device for both environments, requiring fuel that can function effectively in both air and water.

4.1 Air-Water Independent Propulsion Systems

Air-water independent propulsion systems involve separate designs for aerial and underwater propulsion devices, with distinct mechanisms for activation, control, and fuel selection. Due to the physical differences between air and water, the propulsion requirements vary greatly depending on the operating medium. Currently, employing two independent propulsion systems ensures optimal performance in both environments. For aerial propulsion, systems often use conventional turbofan or piston engines, while underwater propulsion typically relies on combinations of batteries, motors, and propellers. For instance, in 2020, Shao Dong of the Chinese Aero Engine Academy [14] proposed a combined propulsion system using gas turbines or piston engines paired with propellers or pumps for underwater propulsion, and turbofan or turbojet engines for aerial propulsion.

Historically, the Soviet Union proposed a flying submarine design in 1934, which combined the functionality of aircraft and submarines. This concept used three 895 kW piston engines for aerial propulsion and a 7.46 kW motor powered by batteries for underwater propulsion. However, due to technological and policy limitations, this project remained in the conceptual phase. Nonetheless, it laid a foundation for the subsequent development of cross-medium vehicle designs [14].

In the 1970s, the United States proposed a large-scale submersible aircraft concept powered by turbofan engines for aerial propulsion and Stirling engines for underwater propulsion [14].

Similarly, in 2008, DARPA introduced a hybrid flight platform concept that aimed to integrate the speed and range of aircraft with the cruising and stealth capabilities of surface vessels. However, the significant technical disparities between aircraft and submarines posed substantial challenges for the project's development [14].

In 2012, Professor Wang Yun's research team at Nanchang Hangkong University [15] proposed a hybrid propulsion system for an air-water drone. The system employed a single-cylinder gasoline piston engine and foldable air propellers for aerial propulsion, and lithium batteries, motors, and water propellers for underwater propulsion. Although this design enabled autonomous operation across mediums, the prototype failed to achieve waterborne takeoff despite successful underwater sealing of the gasoline engine.

Fig. 16. Hybrid propulsion system for air-water drone developed by Nanchang Hangkong University

However, in air-water independent propulsion systems, one propulsion system remains idle during operation in the other medium. The inclusion of two independent systems increases the vehicle's weight, size, and design complexity, significantly limiting its performance.

4.2 Integrated Air-Water Propulsion Systems

Integrated air-water propulsion systems offer advantages in terms of integration, reduced weight, and enhanced operational efficiency, making them well-suited for complex military and civilian applications.

In 2016, Siddall and colleagues at Imperial College London designed the AquaMAV (Aquatic Micro Air Vehicle) [3], [16]. This vehicle used high-pressure gas and a small quantity of liquid to generate thrust by simulating a squid-like jetting mechanism for takeoff and water exit. During operation in both mediums, the system relied on batteries and motors to power a head-mounted propeller. A subsequent 2019 study further improved the propulsion design, though experiments were limited to water-exit scenarios without testing aerial and underwater movements [16].

Fig. 17. AquaMAV water exit concept by Imperial College London

In 2017, the Weisler team at North Carolina State University [16] designed a fixed-wing cross-medium vehicle named EagleRay, and in 2015, Beihang University developed a cross-medium vehicle inspired by the “booby bird” [3]. Both vehicles used a combination of batteries and servo motors for power, utilizing propellers for propulsion when surfacing. These vehicles provided valuable insights into the power system design for subsequent cross-medium vehicles. In 2016, Professor Wang Yun’s research group [17] proposed a design inspired by turbofan engines, which eliminated the central shaft of traditional engines using counter-rotation technology. They installed a metallic water ramjet engine in place of the central shaft, effectively reducing the weight of the power system and achieving efficient dual-mode operation in air and water. Although this design organically integrated two power systems, it did not account for the operational transition between water and air mediums. Moreover, during the transition from air to underwater operation, vehicles using this engine had to pause on the water surface for cooling, negatively impacting operational efficiency and stealth.

In 2022, a research team led by Ang Haisong at Nanjing University of Aeronautics and Astronautics [18] proposed a variable-axis propeller design for cross-medium unmanned vehicles. The system combined brushless DC motors, batteries, air propellers, and water propellers. Other researchers, such as Wang Ge at Harbin Engineering University and Xia Zhijun at the National University of Defense Technology, explored cross-medium ramjet engine concepts powered by oxygen-deficient metal-based fuels, achieving integrated propulsion for both aerial and underwater operations [16].

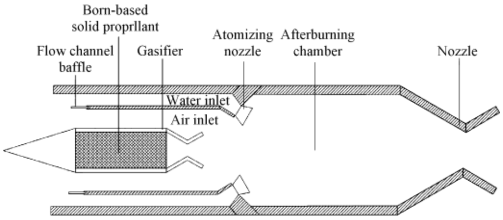

Fig. 18. Preliminary concept of boron-based cross-medium ramjet engine by the National University of Defense Technology

Currently, ramjet propulsion systems for air-water vehicles remain in the conceptual design stage. While theoretical feasibility has been established, significant technical challenges remain, including overall system configuration, thrust regulation, mode transition, and ignition and combustion of metal-based fuels.

5 Conclusion

This paper provides a comprehensive review of the current design and development strategies for trans-medium vehicles. First, it traces the development of trans-medium vehicles, starting from the emergence of the concept, the conceptual design of prototypes, and experimental development, to the successful testing and improvement of prototypes. A brief overview of several notable vehicles from the 1930s to 2022 is included.

Next, it details the development of three commonly used wing design configurations at the current research and development stage: swept wings, multi-rotor wings, and hybrid wings. The performance and drawbacks of representative prototypes for each design are analyzed. As of now, no single trans-medium vehicle design can satisfy all application scenarios. While swept-wing vehicles, owing to their biomimetic principles, show the greatest potential during trans-medium transitions (e.g., entering and exiting water), they face technical challenges in propulsion design, motion control, and endurance. Multi-rotor vehicles, as the most widely used UAV structure, feature relatively mature design technologies. However, achieving more flexible and repetitive medium transitions requires further research on optimizing the weight, size, and control systems of propulsion systems. Hybrid-wing vehicles, though offering relatively lower performance, have shown successful prototype test results, but their design optimization is still in iterative development.

Finally, the propulsion systems of trans-medium vehicles are categorized into two types for analysis: independent air-water propulsion systems and integrated air-water propulsion systems. A comparative analysis reveals that independent air-water propulsion systems often employ separate propulsion systems for air and water, which leads to issues such as low integration, excessive system weight, and long response times for switching between motion modes, making them insufficiently flexible for practical applications. Integrated air-water propulsion systems, with their higher degree of integration, better meet performance requirements. However, battery technology, motor design, and fuel selection for these systems still face significant bottlenecks. The development of air/water ramjet engine technology offers potential for further improving speed, range, and endurance, making it an ideal propulsion method for future air-sea trans-medium weapons. Nonetheless, critical technical challenges must be overcome before it can be applied in actual engineering contexts.

In the future, the design schemes for various forms of trans-medium vehicles remain a subject of further research for scientific teams. Issues such as the selection of materials for vehicle manufacturing, optimization of motion control algorithms, and improvement of efficiency in entering and exiting water present many promising research directions.

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