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Review

Technological Development of Hybrid Aquatic-Aerial Vehicle Based on Bionics: Research Progress and Trends

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Abstract: In both military and civilian domains, the spacecraft is commonly employed to accomplish various tasks. With the ongoing advancements in military strategy and civilian technologies, task environments have become increasingly complex. Consequently, there's a growing trend across all sectors towards integrating water and air operations to enhance task completion. With the continuous progress of biology and mechanics, the development direction of hybrid aquatic-aerial vehicle has emerged in the direction of bionic vehicle. The purpose of this paper is to analyze the current research status and development trend of different hybrid aquatic-aerial vehicles based on bionics. Firstly, the early research and application of hybrid aquatic-aerial vehicles are reviewed by time tracing method. Then, the implications of different biological models for the development of hybrid aquatic-aerial vehicles are analyzed and the research status of different vehicles is discussed. Additionally, the paper analyzes the advantages and disadvantages of hybrid aquatic-aerial vehicles and other vehicle types. It also proposes solutions, primarily focusing on methods for integrating different vehicle types. The current research status, advantages, and disadvantages of various hybrid aquatic-aerial vehicles are analyzed in this paper. It also suggests feasible schemes for hybrid aquatic-aerial vehicles, serving as a valuable research reference in certain areas.

Keywords: Bionics; Historical tracing method; Biology and mechanics; Hybrid aquatic-aerial vehicles

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1. Introduction

In the civil field, tasks such as photography, transportation, data collection, inspection, ocean exploration, ocean search and rescue are accomplished by various types of vehicles such as underwater vehicles and UAV[1, 2]. Meanwhile, in the military field, tasks such as marine strategic resource development, tactical reconnaissance, defense, and offense are basically accomplished by UAVs[3, 4], just as shown in Figure 1.

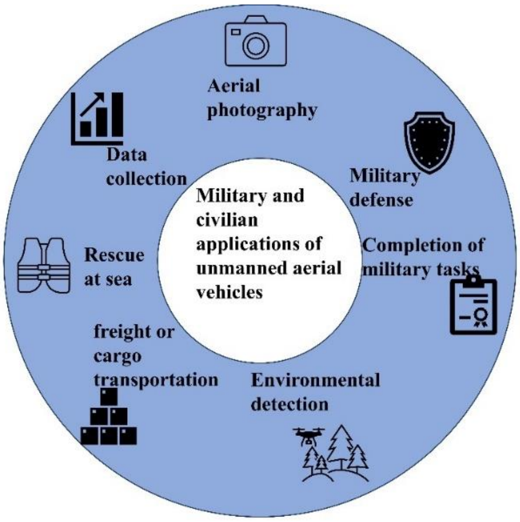


Figure. 1 The broad military and civilian uses of UAVs.

Traditional aircraft plays a huge role in their respective fields, but they can hardly complete cross-domain tasks by themselves. For tasks requiring adaptation to diverse environments, aircraft often needs to collaborate with each other to achieve successful orientations [4, 5].There are higher requirements for the capabilities of aircraft in multi-domain situation awareness, multi-dimensional information fusion, cross-domain penetration attack, etc. With the generation of demand and the development of science and technology, hybrid aquatic-aerial vehicle has been developed. Hybrid aquatic-aerial vehicle is a new type of vehicle that can fly in the air, sail on the surface, sneak under the water and cross the water-air interface. Existing aerial-aquatic vehicles are mainly divided into bionic aerial-aquatic vehicles and rotorcraft vehicles, among which bionic flapping wing vehicles and gliding aerial-aquatic vehicles have been developed in bionics [6]. In addition to bionics based aircraft, aerial-aquatic rotorcraft and other vehicles are also the main research and development directions and have achieved certain achievements[7]. Combining the characteristics of different vehicles, it is able to realize multiple water-air crossings, long-term survival and different environmental missions. Aerial-aquatic vehicles have become one of the most important directions for the future development of military technology. Based on bionics, the research and development on trans-media vehicles have also made progress. For example, we have mastered the deformation, energy storage and flapping models of flying fish and other animals[8]. Bionics provides a key inspiration for hybrid aquatic-aerial vehicles.

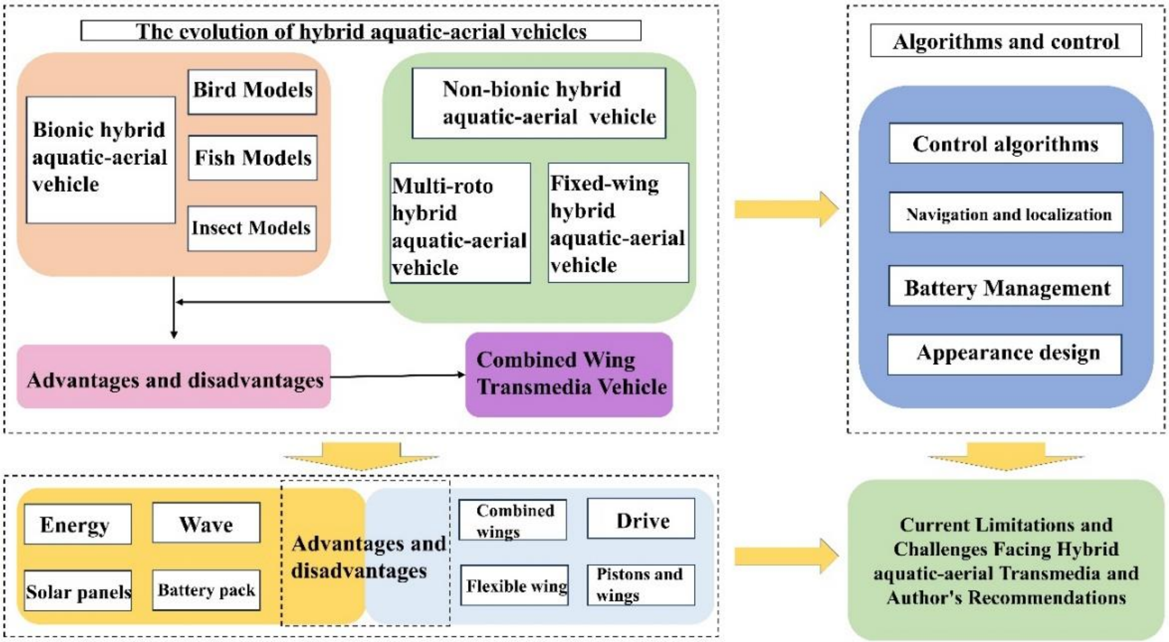


Figure. 2. The flowchart of the essay structure of the paper.

The purpose of this paper is to further advance the field. The flowchart of the essay structure of the paper is shown in Figure 2. In this paper, we firstly review the development history of hybrid aquatic-aerial vehicles by using the time-tracing method. Then, we objectively explain the inspiration of bionics for hybrid aquatic-aerial vehicles and the current status of hybrid aquatic-aerial vehicles. The characteristics, advantages and disadvantages of different hybrid aquatic-aerial vehicles are discussed. Next, the current status of different drive systems of the vehicle and the motion modes of different drive systems are analyzed. Finally, the application of different algorithms to the aircraft is illustrated. Current challenges and limitations in the field are studied. Some potential directions for development are given and some constructive suggestions are made. To some extent, this paper can serve as a guide for the development of the field.

2. History of aquatic-aerial vehicles

The development history of hybrid aquatic-aerial vehicles can be described in four key points, as shown in Figure 3.

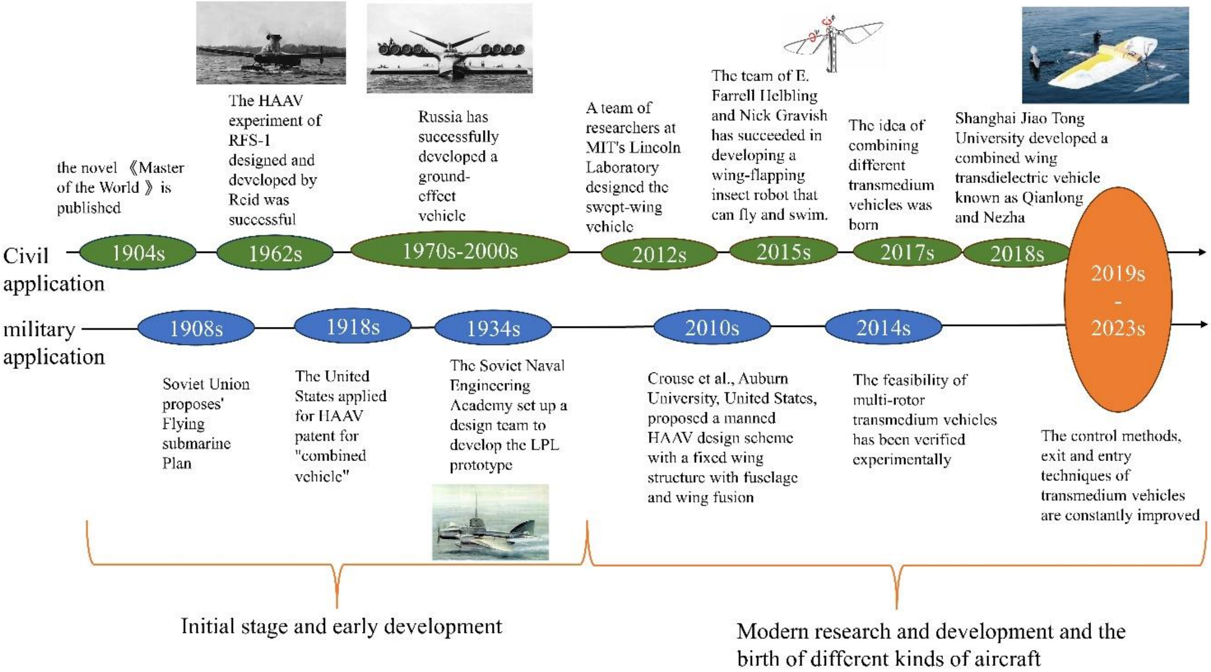


Figure. 3. A rough schematic of the development of Hybrid aquatic-aerial vehicles.

2.1 Initial stage

For the research of aquatic-aerial vehicles, the Soviet Union proposed the "flying submarine program" at an early stage. The Soviet Union then devoted itself to the research of flying submarines. Although the program was successful at a certain stage, it was eventually suspended due to the effects of the war and the limitations of the technology at that time[9].In addition to the Soviet Union, various maritime military powers also pay special attention to the research and development of aquatic-aerial vehicles. The United States applied for a patent for a "combined vehicle" HAAV in 1918 [10]. Since then, researchers and scholars have begun to study hybrid aquatic-aerial vehicles in order to meet the needs of the country.

2.1 Military application

The “LPL” series of flying submarines was the earliest hybrid aquatic-aerial vehicle as well as the most representative result of the Soviet flying submarine program [9]. However, it was too risky to enter intoengineering development at that time, and the Soviet Union stopped the research in this area. After the end of the World War II, the United States and the Soviet Union entered the Cold War. In order to deal with the Soviet Union as a powerful enemy, the U.S. military and General Dynamics formally started cooperation and invested in the development of HAAV[11]. However, due to the fact that the research results did not meet the expectations and the cost was too large, the U.S. was forced to stop the research in this area. Over the next 40 years, even though countries still spend a certain amount of money to carry out research and development. However, the funds invested were not enough to support further research and development, and the invention of hybrid aquatic-aerial vehicles could only be carried out on the basis of existing technologies and achievements. Therefore, the research and development of hybrid aquatic-aerial vehicles have entered a stagnant stage [12].

2. 3 Civil application

In 1962, Reid, an engineer at North American Aviation, designed and developed the RFS-1 HAAV, which successfully completed diving and flight tests in New Jersey[13]. This was the first time that a vehicle successfully completed the conversion of water and air media, and at the same time, the hybrid aquatic-aerial vehicle also officially entered the public field of vision and civil neighborhood.

Subsequently, in the second half of the 20th century, Russia successfully developed ground-effect vehicles (GEOs) that utilized ground effects to fly over water. The most famous of these was the A-90 Orlyonok, but also due to limitations of the technology at the time and the resources consumed in its development, no substantial progress was made. The development of trans-media vehicles remains at a standstill.

2. 4 Modern development

Into the 21st century, the military's needs for maritime reconnaissance, defense and attack have increased and are more focused on naval integration [14-16]. The civil sector has seen a significant increase in the correlation and technological requirements for maritime exploration, rescue, and other missions in two different environments, under the sea and in the air [17, 18]. The continuous progress in various fields makes the requirements for equipment constantly improve, in such an environment has aroused the enthusiasm of most researchers and scholars for the research and development of hybrid aquatic-aerial vehicles.

3. Classification of type

The preceding part of the text basically describes all the types of vehicles currently available, and lists cases of the successful development of various vehicles in the 21st century. We can roughly categorize the vehicles into two types, one is based on the biological models that exist in nature. For example, wing-flapping and swept-back vehicles, which are designed based on the characteristics of animals in nature, are also known as biomimetic trans-media vehicles. The other category is based on the existing underwater vehicles or air drones for the design of the vehicle. For example, multi-rotor vehicles, fixed-wing vehicles, and foldable-wing vehicles [8], which can also be called non-bionic hybrid aquatic-aerial vehicles.The applications, advantages and challenges of different navigation tools are shown in Table 1.

Table 1. Applications, benefits and challenges of different navigational vehicles

Vehicle type	Major application	Specific advantages	Challenges
Birds Vehicle	Undercover reconnaissance、 Airport Bird Repellent	Highly maneuverable and flexible	Short flight times、 Complex wing-fluttering flight mechanism
Squid Vehicle	Underwater exploration、 Environmental monitoring	Advancing in an efficient manner、 Dynamical source of environmental protection	Lack of structural stability of the vehicle
Dolphin Vehicle	High-speed motion research、 Military anti-submarine	Highly maneuverable and flexible、 An efficient way to exercise	Demanding materials needed for navigational vehicles
Flying fish Vehicle	Cross-domain probing、 Disaster relief	Information transfer and interaction across media nodes can be realized	Complexity of motion during medium spanning and gliding
Insect Vehicle	Undercover reconnaissance	Has great concealment、 Has a strong operational	Complexity of control and stabilization issues、 Demanding material requirements
Multi-rotor vehicle	Spraying of pesticides、 Civilian photography、 Transportation of materials	Able to hover、 Simple handling	Weak Adaptation of Multi-Rotor Vehicles in the Face of Transmedia Motion
Fixed wing Vehicle	For underwater concealment and airborne surprise defense	High endurance、 High-speed cruising capability	There is no suitable mathematical model for the fixed-wing transmedia approach to refer to
Combined Wing Vehicle	Military reconnaissance、 Environmental monitoring	Stable cross-media capability	Rationalization of combinations between different navigational vehicles

3. 1 Bionic type of vehicle

Various kinds of animals in nature have very worthwhile mechanical models. For example, the streamlined body shape and swimming form of fish , and the dynamic performance of wing flapping of insects [19]. Many researchers and scholars have studied the characteristics of these animals to design and improve their own designed vehicles [19, 20]. These natural dioramas and kinematic models have provided excellent references for aquatic-aerial navigators.

3. 2 Bird model enlightenment

Birds are able to fly and glide through the sky and can complete the process of feeding from the air into the water and out again. This whole process of entering the water, cushioning the impact, exiting the water, and dewatering the surface are all bionic models that navigators can be relyed on.

3. 2. 1 Birds entering the water

In nature, the feathers of the avian pond goose have an excellent ability to cushion and reduce drag in water. The avian pond geese can to dive to a depth of 10 from a height of 30 meters by diving through the water relying on the inertia caused by its own weight and the ability of its feathers to reduce drag [21, 22]. It is found that there are four main reasons why the avian pond geese are able to do the above motions: (1) the force from mechanical contact is absorbed by the feathers on the surface of the pond goose[23];(2) the avian pond geese is cushioned by multiple air sacs in the interosseous air sacs, cervical air sacs in the neck and thoracic muscles, and intracranial air sacs, as more air sacs than normal waterfowl allow the avian pond goose to have a more powerful cushioning effect into the water [24];(3) the air sacs of the avian pond geese contract after receiving an impact to counteract the large force of the impact [25];(4) the avian pond geese has an excellent streamlined body shape as well as a tail [26].Based on the excellent force model of the Pond Goose, the Aeronautics and Astronautics (BUAA) of Beijing University developed a swept-back wing HAAV, the Bionic Pond Goose I, in 2012 [27]. Bionic Pond Goose I uses a variant swept-back wing for water-air crossing, as shown in Figure 4.

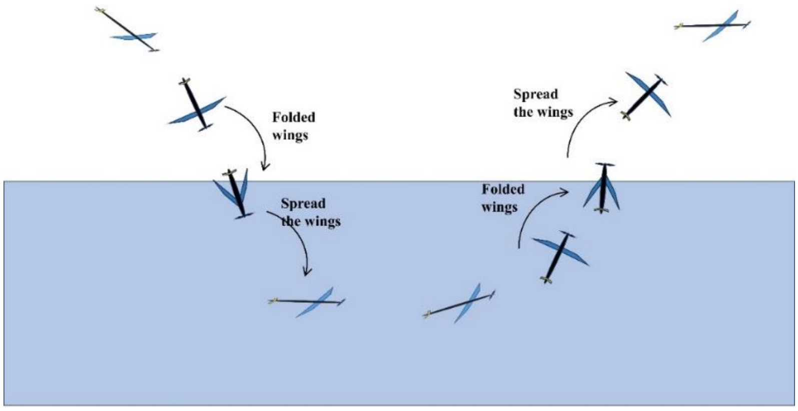


Figure. 4. Schematic diagram of water-air transition of a swept-wing hybrid aquatic-aerial vehicle

Subsequently, based on the water motion model of the Pond Goose and the characteristics of its airbag structure, Aerospace University added apt propellers and onboard airbags. An improved version of the Bionic Pond Goose I, the Bionic Pond Goose II, was developed [28, 29].Pond goose-based bionic aerial vehicles are still in their infancy. Characteristics such as hydrophobic fur, streamlined construction, compressible air sacs, and elastic feathers that allow pond geese to have excellent aerial water entry capabilities [30]have not yet been fully exploited. There are many other birds and birds that have a similar swooping water entry as the Pond Goose. For example, the kingfisher is also one of the most important models used to study hybrid aquatic-aerial vehicle water entry [31].

3. 2. 2 Birds out of the water

The primary form of bird emergence and takeoff from water or air is the use of wing beats on the water surface, which is the reference model for flap-wing vehicles [32]. Accelerating a vehicle from water to air across a medium by accelerating it directly over water or in water is extremely energy-intensive and not very practical[33].Faced with the high-consumption takeoffs of the former, the more aerodynamically advantageous flapping-wing vehicle [34] turned out to be a better choice for research and development. With the help of two forces, birds such as pigeons take off by beating the air with their wings while jumping on the ground[35]. Similarly, cormorants take off on the surface of the water using their webbed feet to paw the water while using their finned limbs to slap the surface. The two different behaviors together not only reduce the burden on the wings but also contribute to their takeoff movement[36],as shown in Figure 5.And scientists have designed certain bionic models based on this takeoff model[37]. Currently, flap-winged underwater navigators and flap-winged navigators have been designed respectively [38].Since birds operate by bending their joints to flap the air and water surface so we need to develop wings with flexible membranes with passive dynamic deformation properties, which is one of the key difficulties faced by flap-wing navigators[39].

Figure. 5. Descriptive diagram and force analysis of a pond goose taking off at the surface of the water.

3.3 Fish model

With the help of the acceleration of their own tail fins , dolphins and flying fish can accelerate their speed out of the water. Flying fish can also use their caudal fins to slap the surface of the water again as they return to the surface to take off again, thus accomplishing continuous airborne gliding. These phenomena have attracted scholars related to hybrid aquatic-aerial vehicles to conduct research.

3. 3. 1 Squid ejection model

In 2016, Ortega Ancel et al. designed the AquaMAV with reference to squid catapult takeoff [40]. The squid is able to expell water to be strongly as a way to obtain a huge power to accomplish the ejection motion[41]. The squid can also swim in the subsequent motion to recharge water to help it complete the next ejection [42].Ortega Ancel's research team referenced the squid's ejection method by using high-pressure CO2 as a thrust to launch the CO2 within 1s to complete the vehicle takeoff [40],as shown in Figure 6.

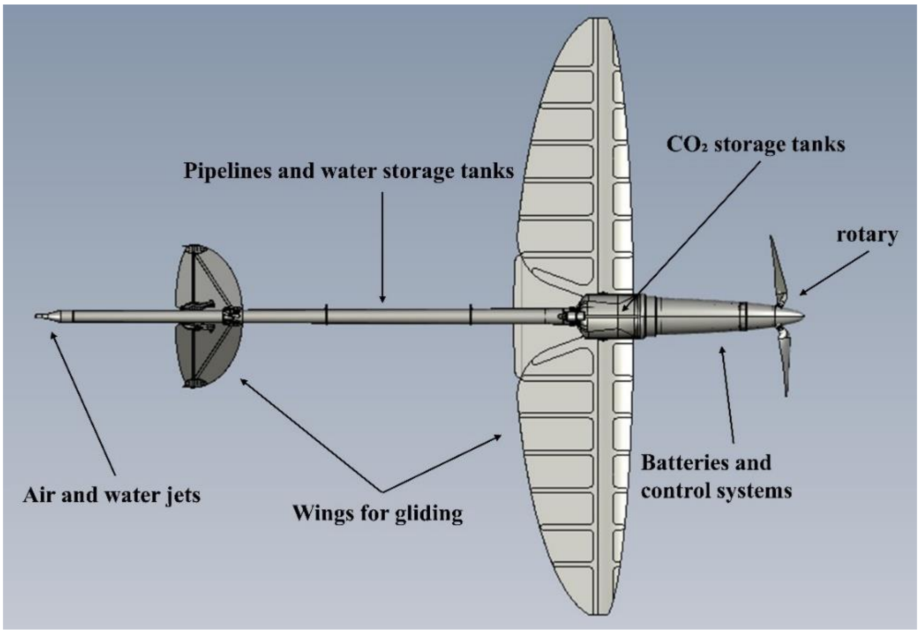


Figure. 6. Schematic diagram of AquaMAV structure.

3. 3. 1 Dolphin acceleration model

Dolphins accelerate through the water by swinging their tail fins, which is a more aerodynamic method than the squid's jet acceleration. The dolphin's body structure is also well suited for the crossing of two different media, water and air. Under certain circumstances, dolphins are able to glide through the air for short periods of time. Researchers and scholars at Hybrid aquatic-aerial Vehicles have conducted studies based on biological models of dolphins. Zongshuai Su et al. in 2016 calculated the minimum exit velocity that allows a dolphin to fully leap out of the water. They constructed a self-contained jumping dolphin robot with commercially available actuators and power supply for the first time [43]. This was followed by a control strategy for repetitive jumping of a dolphin robot in 2019 [44].With the basis of dolphin motion, significant achievements have been made in the development of aquatic-aerial navigators [45, 46].In addition to dolphins, there are many other fish in the ocean that move in the similar way, just as the shark. Researchers have constructed a shark-releasing robot from a biological model of a shark, as shown in Figure 7. With complex biological models, scientists still need to study them in more depth.

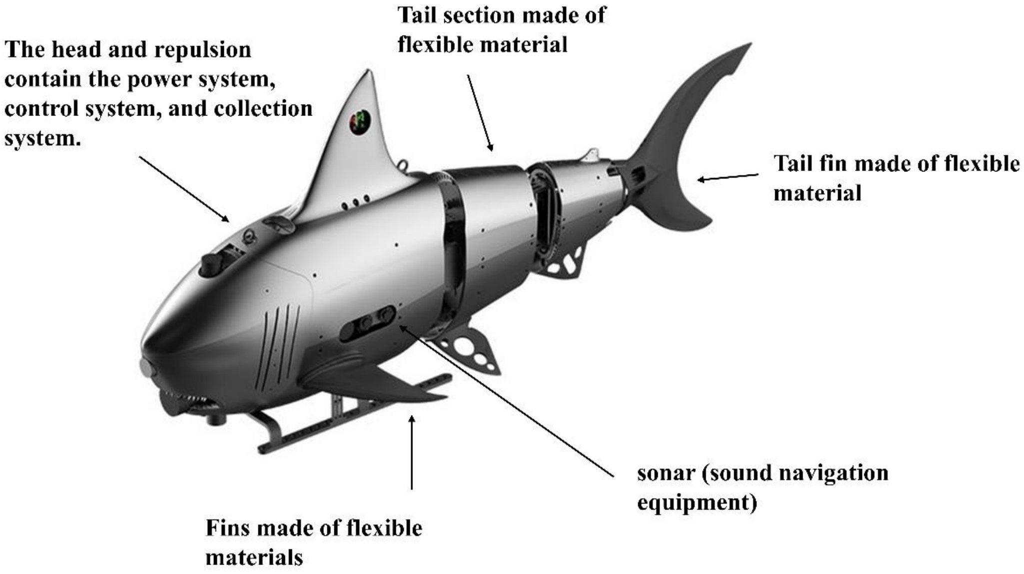


Figure. 7. Bionic Shark Vehicle Structure.

3. 3. 3 Flying fish "surface gliding" model

The water launch of a flying fish is one of the bionic objects of hybrid aquatic-aerial vehicles [47]. The flying fish accelerates its body by rapidly swinging its tail fin during the takeoff out of the water. When the body accelerates to the desired speed (10 m/s), the body of the flying fish surfaces. At this point, the flying fish continues to keep its caudal fin oscillating in the water at a certain frequency to maintain its locomotion [13]. As the fish continues to accelerate and reaches higher speeds (20 m/s), the fish leaves the water surface. While in the air, the flying fish spreads its oversized pectoral fins and glides within 1 m of the water surface. This state helps it to glide unpowered through the air for hundreds of meters. As the flying fish re-contacts the surface of the water it can either sink into the water or swing its tail fins again for a second flight [48, 49],as shown in Fgure 8, in which the diagram on the left depicts a flying fish gliding off the surface of the water after accelerating to a certain speed, the diagram on the right shows the force analysis of the flying fish as it accelerates through the water. Based on the out-of-water motion of the flying fish and the re-takeoff motion of the flying fish touching the water, a flying fish model was designed and tested by Gao et al. in 2011. And researchers also developed a design solution for a flying fish robot from a mechanical design perspective [50].Studies of the flying fish model and the dolphin model above have demonstrated to us the feasibility of the scheme of swinging the caudal fin to accelerate itself out of the water. However, the method of simulating a flying fish out of the water currently exists only on a theoretical basis, and the model has not yet been successfully applied to the development of hybrid aquatic-aerial vehicles.

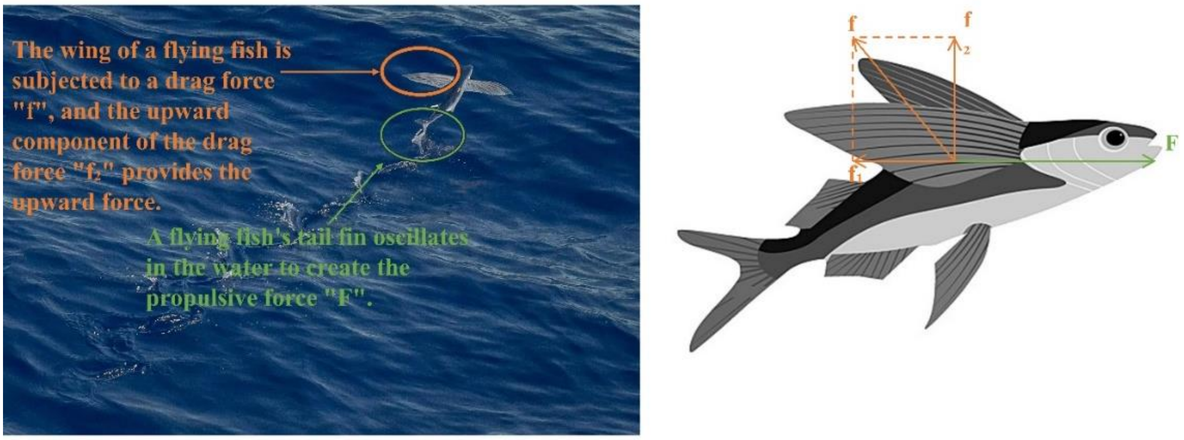


Figure. 8. Flying fish

3.4 Insect model

Based on the principle of insect flight, scholars of aquatic-aerial navigators began to improve flapping-wing navigators . By 2013, a flapping-wing navigator with a vibration frequency between 120-160 Hz, was designed[51]. Subsequently, in 2015, a team of researchers showed that by using computational fluid dynamics (CFD) simulations, lowering the underwater flapping frequency could achieve a flow distribution and dynamic performance similar to that of air. The first flapping wing HAAV was successfully developed. But due to the tension and lift is several times the weight of the vehicle itself. The vehicle can only accomplish aquatic-aerial motion from air to water [52]. Finally in 2017 the research team improved four aspects of the wing shape, flapping frequency, fuselage balance and the installation of a collector box to make the flap-wing HAAV have the ability to take off from the water and cross into the air [6].Insects are used as a model for flying vehicles by utilizing the resonance phenomenon of wings to reduce energy consumption. This allows the vehicle to fly, dive and move across domains with less energy. The biggest advantage of utilizing the resonance phenomenon to greatly reduce energy consumption is also the biggest difficulty.

3. 5 Non-bionic hybrid aquatic-aerial vehicles

3. 5. 1 Multi-rotor vehicle

As early as 2014, a scientific team led by Drews et al. from the Federal University of Rio Grande do Sul assembled four water propellers and four air propellers on their multi-rotor HAAV. These eight propellers were used for different environments. This is the first time that a multi-rotor HAAV has been successfully validated for its feasibility [24]. However, the separation of the two different drives, aerial and underwater, increased the weight of the vehicle itself. This makes the multi-rotor vehicle's range and its own performance decrease to some extent [53].However, this problem was solved by Alzu'bi et al. from the University of Auckland. They proposed an air-water compatible propulsion scheme in response to Drews et al.'s research results and problems. This scheme changes the rotational speed of the propeller so that the propeller of the vehicle can be adapted to different environments and fulfill the propulsion tasks in different environments. And based on this, a prototype Loon Copter was designed[54]. However, the improved navigator still faces the problem of falling back to the water surface after takeoff because the rotor speed is not fast enough. Subsequently, the U.S. Navy funded Rutgers University, where a team of researchers developed the navigator, a two-layer, coaxial, eight-rotor, top propeller and bottom propeller separated unmanned aerial vehicle. The top propeller in the gas and the bottom propeller in the water will change the rotational speeds of the propellers according to the different environments in which they are located when the navigator exits the water. In order to accomplish the mission of water emergence, this structure of separate top and bottom propellers solves all the problems mentioned above[7, 55, 56].The water flow is shown in Figure 9.

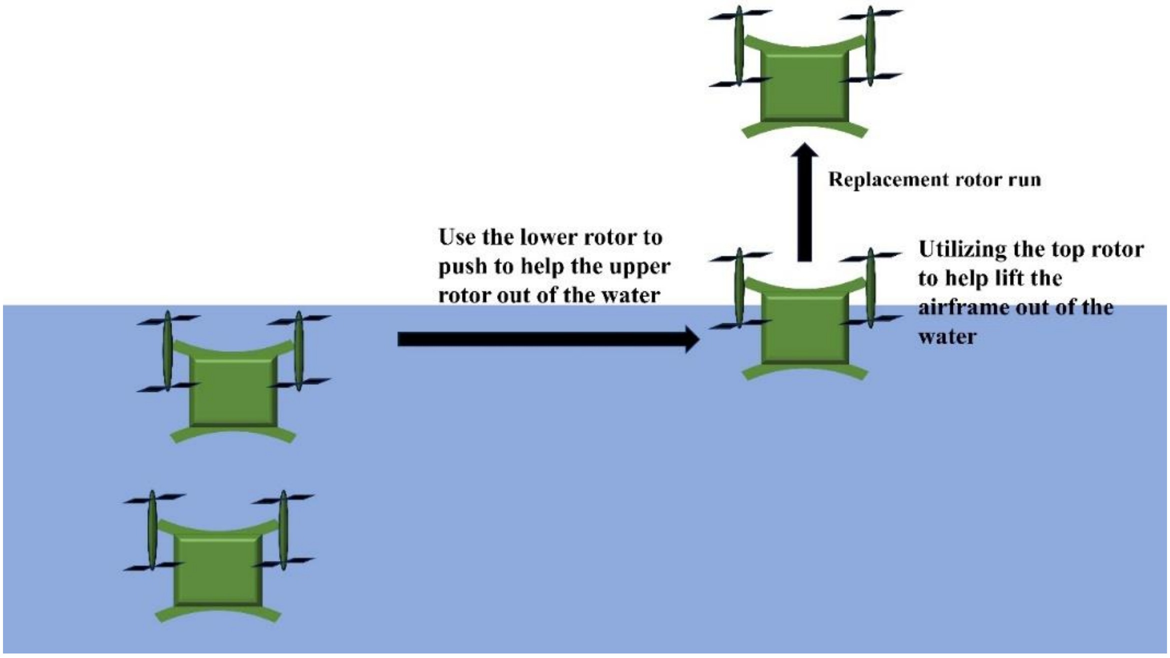


Figure. 9. Schematic of a double-decked multi-rotor hybrid aquatic-aerial vehicle out of the water

3. 5. 2 Fixed wing

Aquatic-aerial manned vehicles are much more difficult to develop than aquatic-aerial unmanned vehicles. For the current level of technology, aquatic-aerial unmanned vehicles are much simpler in structure. The advantages of not needing to consider personnel carrying and survival systems make the unmanned fixed wing more feasible. Considering the above, the U.S. Naval Institute prioritized the development of a test model of a fixed-wing vehicle, "test Sub", in 2014 [57]. Fixed wings have two problems due to their structure:(1) the larger weight of the vehicle results in a larger force of gravity, and the vehicle needs to expend additional energy to equalize the force of gravity;(2)vehicles with less weight and more buoyancy can only navigate on the surface of the water and cannot accomplish underwater navigation. Currently, there are three solutions to the two problems mentioned above.

(1) Referring to the submarine's water compartment design [58], the wings and fuselage are designed to be hollow. The same method as the submarine is used to balance the buoyancy and gravity by changing the overall density of the vehicle through water inlet and outlet [17, 59],as shown in the figure 10.

(2) With the replacement of fuselage and wing materials, t the effects of gravity and buoyancy can be reduced.

(3) The wing of a fixed-wing vehicle can be designed as a flapping propeller. The motion of the wing flaps is used to balance gravity and buoyancy in the water as well as to accomplish propulsion tasks in the water[60].

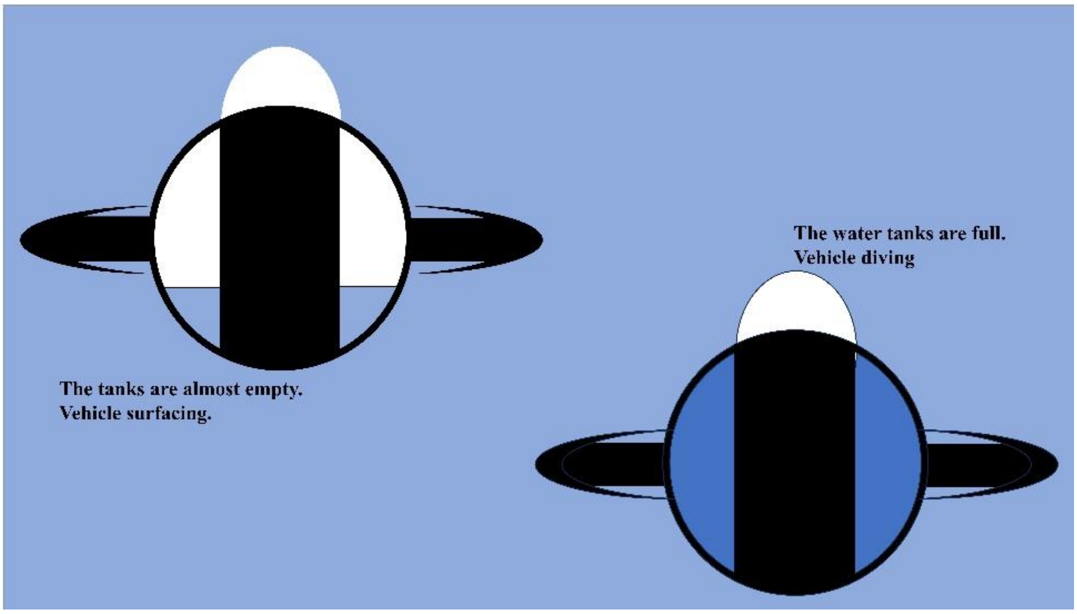


Figure. 10. Fixed-wing hybrid aquatic-aerial vehicle proposal for up and down dives in water.

3.5.3 The combination of the vehicle

The above vehicles have their own advantages and disadvantages.These are the existing disadvantages and challenges that researchers and scholars are currently trying to overcome. In addition to improving the fundamental conditions such as vehicle technology and materials, it is also possible to combine different vehicles. The combination of different vehicles can make up for their shortcomings by utilizing the advantages of other vehicles. It is also possible to combine the strengths of vehicles to improve their performance.

First, in 2017, a research team from China's Shanghai Jiao Tong University released the Nezha series of combined-wing navigators. The vehicle is combined with three power systems: fixed-wing, multi-rotor and aerodynamic buoyancy. The simultaneous presence of all three powertrains makes it easier for the vehicle to take off by fully utilizing the lift generated by aerodynamic and energy propulsion. The existence of multiple power systems also reduces the energy consumption of the vehicle to accomplish various maneuvers. In addition, the vehicle has the characteristics of different vehicles. For example, the vehicle can perform the hovering function unique to fixed-wing. It can fulfill the gliding function unique to fixed-wing [61-63]. Subsequently, Shanghai Jiaotong University modified "Nezha" by equipping it with a lightweight aerodynamic system, matching it with a kinematic arm, and improving the control method, so as to provide it with better underwater performances such as deeper dive depths and stronger resistance to fluctuations [62, 64]. The development of the combined wing is now possible to start directly from the navigator itself. The method of upgrading and improving the hybrid aquatic-aerial vehicle with the help of the characteristics of different vehicles. The combination of different vehicles is characterized by easier and more fruitful results than the underlying aspects such as the adoption of materials and new control systems.

4 Drive

The motion efficiency, influencing factors, current status and feasibility of different drive systems are shown in Table2 .

Table 2. Table example that covers the width of the page.

Driver Type	Inlet and outlet water efficiency	Influencing factors	Current state	Low feasibility
Wave energy drive	Weak medium spanning ability and poor energy utilization	Propulsion performance，Speed of navigation	Mainly used for prolonged floating at sea to collect information	Low feasibility

T**able 2.** Table example that covers the width of the page.

Driver Type	Inlet and outlet water efficiency	Influencing factors	Current state	Low feasibility
Combined wings	Strong medium spanning ability and high energy utilization efficiency	Design Layout， Material Selection	Used to make a difference in a variety of industries	High feasibility
Flexible wing	Strong medium spanning ability and high energy utilization efficiency	Design of the control system. Rigid-flexible coupling dynamics	Mainly for military camouflage reconnaissance High feasibility	High feasibility
Pistons and wings	Weak medium spanning ability, but more efficient energy utilization	Material Selection， Speed of navigation， Propulsion performance	Currently slow to develop	Medium feasibility

4. 1 Wave energy drive

The wave energy glider, one of the newest energy vehicles of the 21st century, was first prototyped as a wave glider by Roger Hine in 2005 [65].The wave glider consists of two parts one floating on the surface of the water and the other gliding under the water, which are connected by a flexible thin rope [66]. The two parts have different structures and the underwater part can emit sound waves to collect underwater conditions in the target area. This information can be used to serve meteorological observation, fishery management, topographic surveying [67, 68], etc. in the field of livelihood, and in the military, it can collect information about hostile submarines to serve various combat missions. The waterborne part is responsible for receiving instructions from the controller and transmitting the collected information [69],as shown in Figure 11.

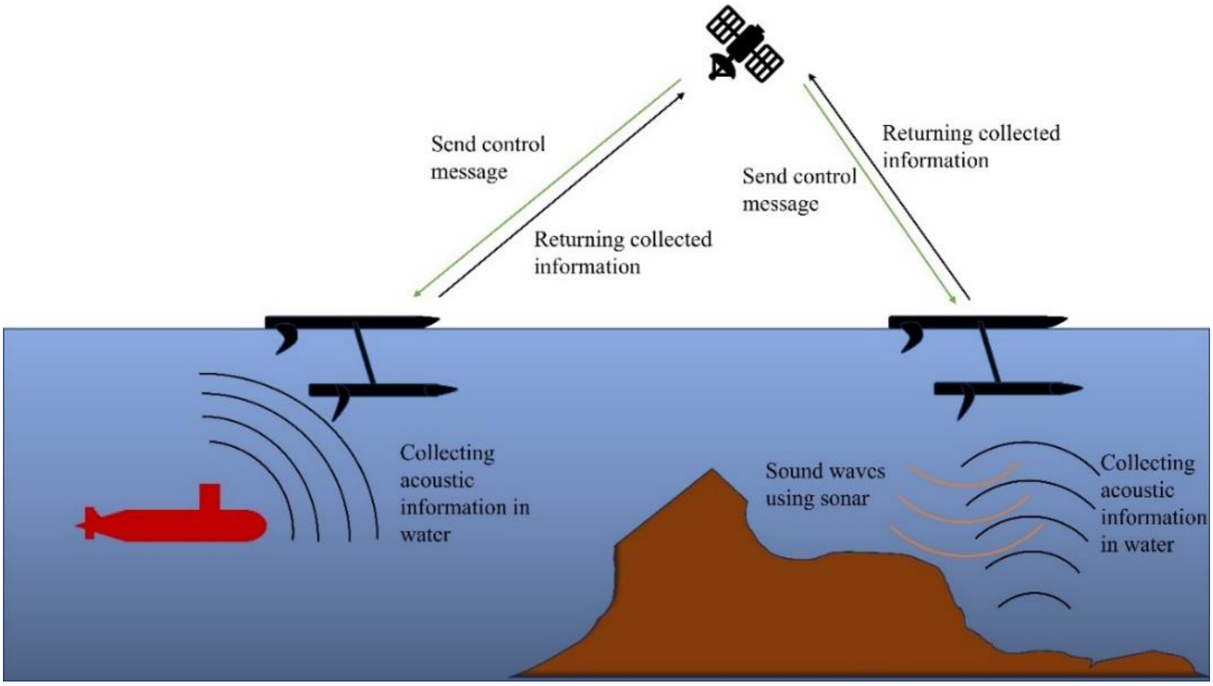


Figure. 11. Schematic diagram of a wave glider collecting and transmitting information

A wave glider's movement is facilitated by two distinct sections, which also play a role in the collection and transmission of data. The surface section moves in sync with the ocean's surface waves, while the underwater section is connected to the surface section by a flexible tether. This tether allows the oscillation of the surface section to drive the underwater hydrofoil up and down, generating forward thrust. This coordinated interplay between the two sections is how the wave glider harnesses wave energy to propel itself [70],as shown in Figure 12.

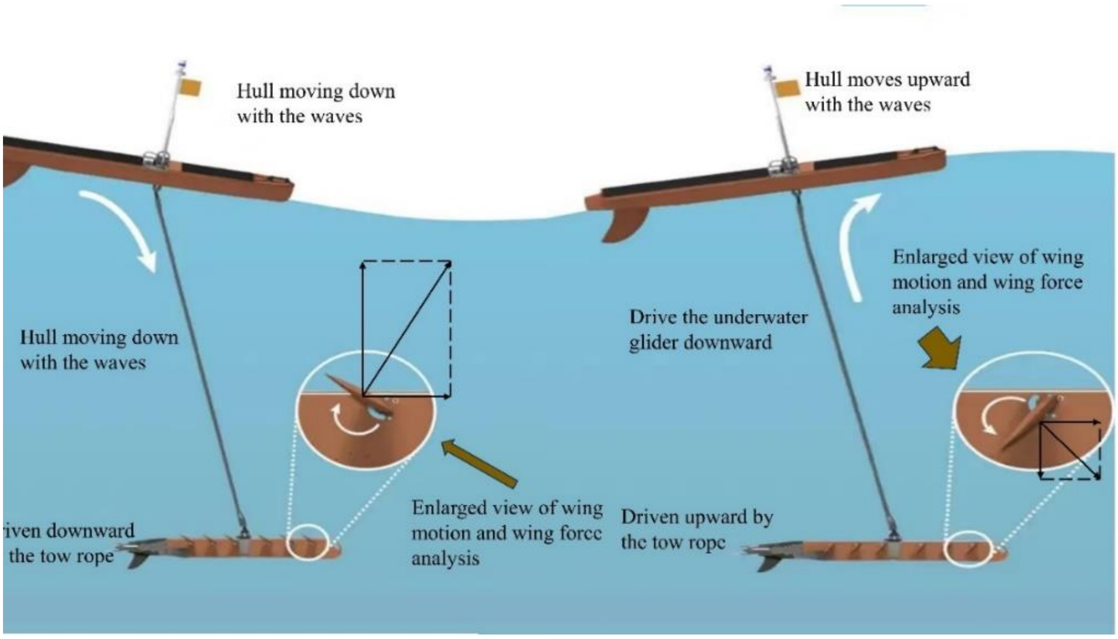


Figure. 12. Descriptive diagrams of the motion of a wave glider in the water and force analysis of the wing.

Due to the variability of wave energy and the influence of wind direction, the path and speed of wave energy gliders are unpredictable[71]. To address these issues, scientists have proposed solutions on two fronts: (1) installing controllable propellers for the glider, which can be adjusted in terms of rotational speed and direction to change the glider's course or control its flight speed[72, 73]; (2) installing multiple rotors, allowing the glider to perform flight maneuvers similar to those of an unmanned aerial vehicle (UAV). This approach combines the extended range of UAVs with the agility of wave gliders [74, 75].

4. 2. Combined wings

The Nezha III, part of the "Nezha" series designed by Shanghai Jiaotong University, exemplifies this approach by integrating various drive systems. This integration allows the Nezha III to execute a range of maneuvers, including horizontal flight, hovering, underwater gliding, and transitioning between water and air [76].

(1)Horizontal flight: First, the rotor rotates at a specific rate, enabling the aircraft to take off or to hover vertically. Once airborne, the rotor's speed is increased to a certain level, after which the airframe is tilted forward to produce forward thrust. Following this, the fixed wing starts to generate lift. This lift counteracts a portion of the gravitational force. When the aircraft reaches a certain speed, the fixed wing generates a lift force that completely counteracts the force of gravity. Achieving this balance between thrust, drag, gravity, and lift allows the vehicle to engage in stable horizontal flight .

(2)Hovering and vertical takeoff: Only the rotor blades provide upward lift. The hovering state, which is relatively stationary, is suitable for tasks such as filming and sampling [77].

(3)Underwater Gliding: The only driving force during underwater thrustless gliding is the horizontal component of lift, resulting from the inequality between gravity and buoyancy. During the glide, the vehicle can change its buoyancy by filling the external bladder with compressed gas from the internal cylinders, or by pumping gas from the external bladder into the internal cylinders. Simultaneously, the vehicle's elevation angle changes as the internal density changes. Consequently, the wing's elevation angle also changes, thereby altering the horizontal component of lift. This alteration controls the rise or dive of the vehicle in the water [76].

(4) Water-air transition: Vehicles equipped with rotor blades are more likely to employ vertical takeoff and landing (VTOL) capabilities for water-to-air transitions. This process is powered by the rotor, which provides the lift necessary to complete the transition. A vertical transition maintains a more stable attitude and speed throughout the process, reducing both the drag force upon exiting the water and the impact force upon water entry.

4. 3 Flexible wing

The key to realizing such vehicles lies in the development of flexible wings, which permit some bending of the foil [78].

(1) Underwater motion: The bionic flapping-winged vehicle obtains its driving force underwater in a similar way to how a sea turtle uses its forelimbs or other fish use their fins for propulsion. Generating propulsive force by flapping its foils, the vehicle produces thrust that drives it forward. It is also possible to alter the vehicle's motion by changing the direction of the propulsive movements created by the separate foils [79, 80].

(2) Aerial motion: Similar to underwater motion, in the air the vehicle also gains propulsion by flapping its foils. However, unlike in water, there is no buoyancy. To achieve aerial motion, the vehicle must increase the rate of foil flapping to counteract gravity. Additionally, the vehicle is more susceptible to interference from other foils in the air and needs to adjust the flapping frequency or foil size to counteract turbulence, ensuring better flight performance[81, 82].

(3) Water-air spanning: Hybrid aquatic-aerial vehicles face challenges when transitioning from air to water, particularly when the vehicle's mass is insufficient to penetrate the water surface or is so large that it results in a significant impact upon entry. Y Chen et al. addressed the issue of excessive impact during air-to-water transitions by applying a surfactant to the vehicle's surface . Micro-vehicles confronting the challenge of water-to-air transitions must also contend with substantial water surface tension. Increasing the flapping frequency of the wings underwater can lead to wing damage. To mitigate this, Y Chen et al. proposed a two-step process for water-to-air transitions: first, leveraging buoyancy to emerge the craft from the water, followed by the use of a pulse system [83, 84] or a chemical reaction jet to generate propulsion . Once the craft is pushed out of the water, the flapping wings take effect to maintain airborne flight .,as shown in Figure 13.

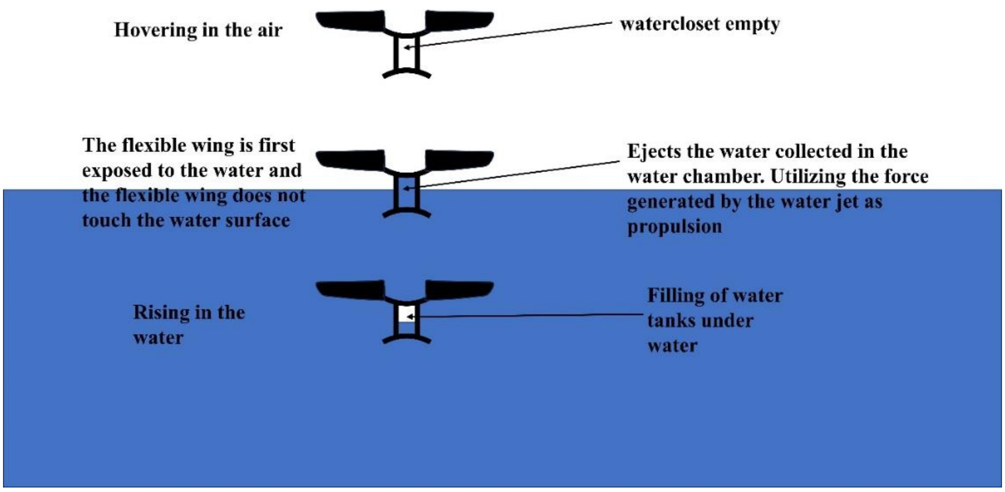


Figure. 13. Schematic diagram of a flapping-wing hybrid aquatic-aerial vehicle crossing from water to air

4. 4 Pistons and wings

Vehicles that utilize both pistons and wings are initially propelled by pistons, which ignite compressed gases and liquids to transform them into thrust [85]. Subsequently, the wings are employed to alter the direction and magnitude of the force acting on the vehicle, aiding in its stabilization whether airborne or submerged [86]. These vehicles commence motion in a similar fashion while at rest: they are accelerated by a piston on the ground, at the surface, or in the water. Initially, the wings are aligned flat with respect to the direction of motion to minimize drag from air or liquid. Once the vehicle reaches a certain speed threshold, the wings are then adjusted to form an angle with the direction of acceleration. This modification helps to redirect a portion of the drag force vertically, facilitating the vehicle's ascent or descent.

5 Algorithms and control

5. 1 Model predictive control

Model Predictive Control (MPC) for UAVs is an advanced control strategy. So MPC is widely used in the fields of attitude control, path planning and obstacle avoidance of UAVs. Rabab Benotsmane Optimized Energy Consumption of a Vehicle Using MPC[87]. Ruochen Xue proposes an output feedback stochastic model predictive control (MPC) algorithm to generate an optimal control sequence with less conservatism by considering the uncertainty caused by the disturbance distribution information and attitude tracking error. The closed-loop probabilistic constraint satisfaction, recursive feasibility and stability of the algorithm are further demonstrated[88].

Model predictive control fundamentals

(1) Predictive Modeling: a model predictive control system will predict the behavior of the system over a future period of time based on a dynamic model of the system. The dynamics of the system can be modeled as a single hybrid aquatic-aerial vehicle or as a cluster of hybrid aquatic-aerial vehicles [89].

(2) Objective function: the system defines a performance metric. This function is usually a function of the deviation between the output of the system and the desired value [90]. The function may also include a penalty term to control the input.

(3) Constraint handling: ensuring that the system state, control inputs, etc. within the prediction horizon satisfy specific constraints [91].

(4) Online optimization: the optimal control input sequence is obtained by solving an optimization problem during each control cycle [92].

(5) Rolling optimization: in practice, only the first control input is implemented, and then the optimization is repeated in the next control cycle [93, 94].

Nowadays most scientists almost always use the following algorithmic process [89, 93, 95, 96] regardless of the algorithms and models used to improve and use modeled control systems for hybrid aquatic-aerial vehicle:

(1) Modeling: the experimenter establish a mathematical model of the controlled system, usually a linear time-varying model or a nonlinear model.

(2) Design objective function: the experimenter design the objective function according to the control objectives, including tracking error, control energy consumption and so on.

(3) Setting constraints: the experimenter sets function constraints including input-output constraints, state constraints, etc.

(4) Solving the optimization problem: At each control cycle, the experimenter solves the control input sequence by numerical optimization methods (e.g., quadratic programming, interior point method, etc.) using the predictive model and objective function.

(5) Implementing the control: the experimenter applies the first element of the obtained control input sequence to the system.

(6) Repeat optimization: in the next control cycle, the above process is repeated, taking into account the latest system state and measurement information.

5. 2 Simultaneous localization and mapping

Simultaneous localization and mapping (UAV SLAM) is a technology for autonomous navigation and map construction by hybrid aquatic-aerial vehicle in unknown environments.As technology continues to advance, the accuracy and robustness of SLAM systems are improving [97, 98], providing strong support for autonomous navigation and interaction of hybrid aquatic-aerial vehicles. Rodrigo Munguía's vision-based simultaneous localization and mapping system applies SLAN to unmanned aerial vehicles[99].

Operation of SLAM. The flowchart is shown in the figure 14.

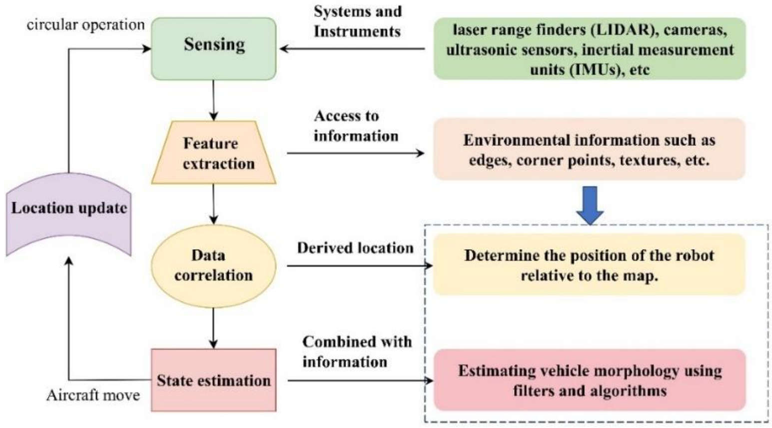


Figure. 14. Flowchart of SLAM.

(1) Sensing: the SLAM system uses a variety of sensors to sense the environment, such as laser range finders (LIDAR), cameras, ultrasonic sensors, inertial measurement units (IMUs), etc [100].

(2) Feature extraction: useful features such as edges, corner points, textures, etc. are extracted from the sensor data, which are used for subsequent localization and map construction [101].

(3) Data correlation: matching newly perceived features with those in a previously established map to determine the robot's position relative to the map [102]. Feature extraction and data association can be done together with convolutional neural networks (CNN). Figure 15 shows a typical convolutional neural network framework.

(4) State estimation: filters (e.g., Kalman filtering, particle filtering) or optimization methods (e.g., nonlinear least squares) are used to update the robot's position estimates and maps [103].

(5) Map update: Updates the map based on new positional estimates and sensory data.

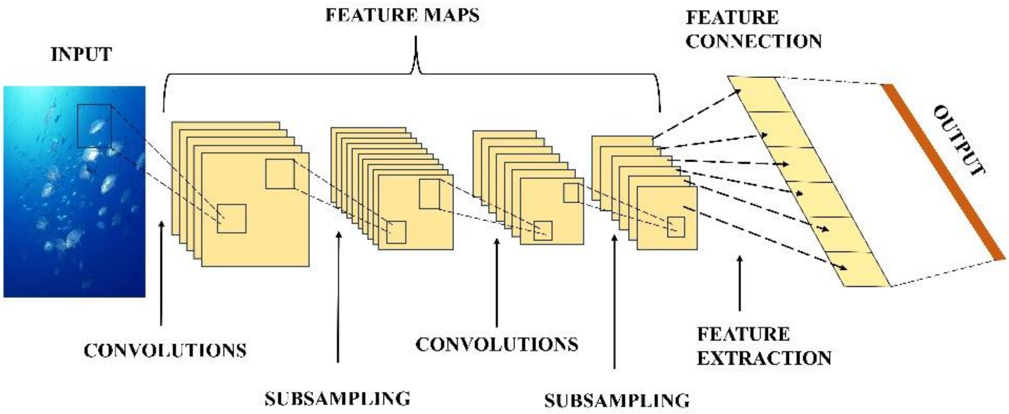


Figure. 15. Typical CNN architecture.

5. 3 Battery Management System

Battery Management System (BMS) is an electronic system used to monitor and protect rechargeable batteries (e.g., lithium batteries, lead-acid batteries, etc.). It usually consists of both hardware and software components to ensure that the battery can operate safely and efficiently and maintain optimal performance over the battery life cycle [104]. For hybrid aquatic-aerial vehicle battery management systems can also help to monitor the remaining power and predict the available hours, helping hybrid aquatic-aerial vehicles to plan mission schedules based on the mission and remaining power[105].

5. 4 Appearance design

5. 4. 1 Computational Fluid Dynamics (CFD)

CFD techniques can predict and analyze real or hypothetical fluid flow situations without the need for physical experiments, thus playing an important role in engineering design, scientific research, and technological innovation. Computational fluid dynamics can help to design a rational airframe structure for hybrid aquatic-aerial vehicles by studying the flow characteristics of two different media, liquid and air [106]. At the same time, it can accurately display the distribution of the flow field around the inlet and outlet objects, and analyze the dynamic process of the air cavity and liquid splashing, etc. Cross-media motion analysis using CFD methods can provide valuable theoretical insights into the design of novel aircraft configurations. With this guidance, Andrew T. Wick simulates and analyzes the overall splashdown process of his newly designed unmanned aerial vehicle (UAV) as it falls into water from various altitudes[107]. The following processes are usually performed in computational fluid dynamics:

(1) Pre-processing: defining the region of fluid flow (geometric modeling) [108] and dividing it into a mesh (grid generation). The mesh can be 1D, 2D or 3D depending on the complexity of the problem [109]. The Random Forest algorithm consists of multiple decision trees arranged in an integrated manner. However, individual decision trees are useful for fluid modeling, e.g., the random tree algorithm is useful for hydraulics modeling. Figure 16 shows a simple example of the random forest algorithm.

(2) Physical model selection: appropriate physical models are selected based on the characteristics of the fluid flow, including turbulence models of the fluid, heat and mass transfer models, etc .

(3) mathematical modeling: the institute can use a variety of equations in establishing the mathematical model of fluid flow, such as the Navier-Stokes equations based on conservation of mass, conservation of momentum and conservation of energy [110].

(4) Numerical solution: the equations are discretized using numerical methods (e.g., finite difference method, finite volume method, or finite element method) and solved on a computer [111, 112].

(5) Post-processing: the results obtained from the analytical solution, which usually include flow field visualization, pressure and temperature distribution analysis, etc., to obtain an in-depth understanding of the fluid flow characteristics.

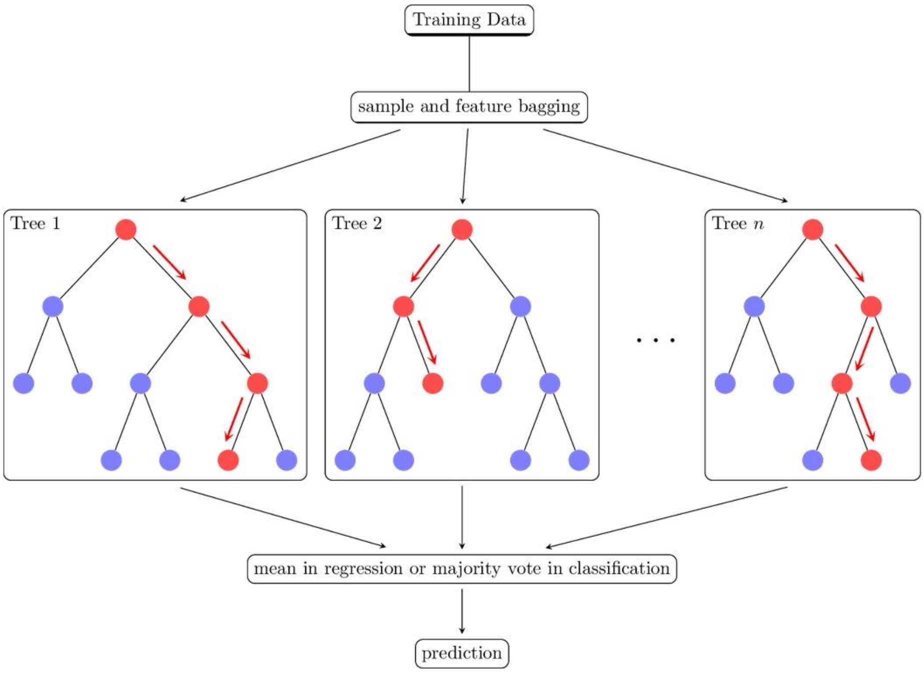


Figure. 16. Simple example of the Random Forest algorithm. Two different colors are used to highlight feature selection. For each node of the decision tree, a subset of elements is randomly selected at the node. Yellow triangles indicate the subset of selected elements.

5. 4. 2 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) of a vehicle is a process of modeling and evaluating the structure of a vehicle using mathematical methods [113]. This method works by discretizing the structure of a vehicle into a series of small elements (e.g., triangles, quadrilaterals, or other shapes), which are then used to create a mathematical model of the entire structure [114].

Finite Element Analysis (FEA) plays an important role in aircraft design and development, especially in ensuring structural strength, stiffness and stability [73].

The analytical process of FEA:

(1) Pre-processing: Defines the geometry of the problem and divides it into a finite element mesh. The mesh can be one, two or three dimensional, depending on the dimension of the problem.

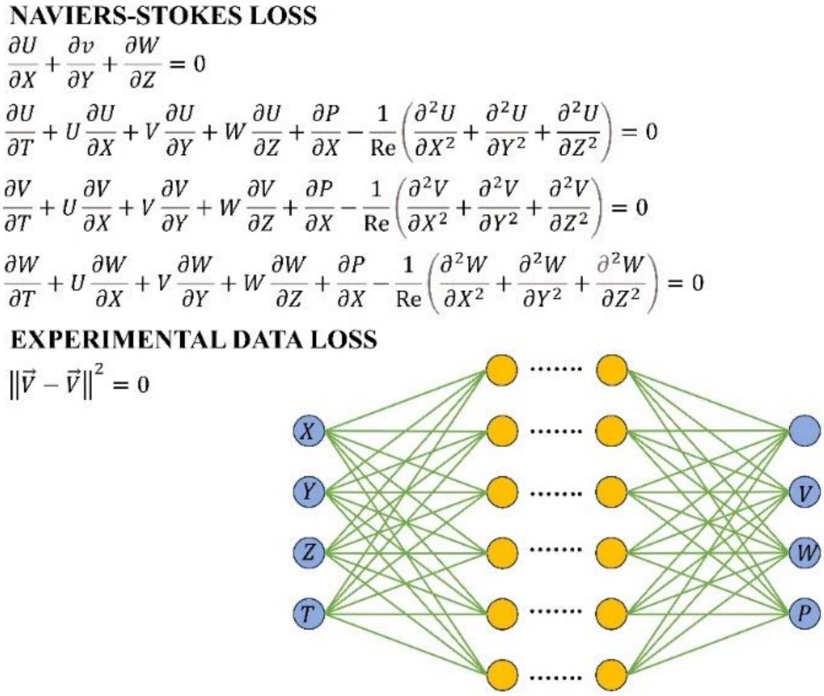
(2) Selection of element type: According to the nature of the problem and the accuracy requirement of the solution, select the appropriate type of finite element, such as linear element, quadratic element, etc.

(3) Mathematical modeling: The Institute can use a variety of equations in mathematical modeling of fluid flow, such as the Navier-Stokes equations based on conservation of mass, conservation of momentum, and conservation of energy [68].The algorithm for solving the Navier-Stokes equations is shown in Figure. 18.

(4) Establish equations: Establish equations on each element according to the laws of physics (e.g., equilibrium equations, eigenstructure relationships, etc.) to form a set of equations for the entire problem.

(5) Numerical solution: Use numerical methods (e.g., iterative method, direct solution method, etc.) to solve the system of linear or nonlinear equations formed.

(6) Post-processing: Analysis of the results obtained from the solution, usually including visualization of the distribution of stress, strain, temperature, velocity, etc., as well as further processing and analysis of the results.



NAVIERS-STOKES LOSS

$$\frac{\partial U}{\partial X}+\frac{\partial v}{\partial Y}+\frac{\partial W}{\partial Z}=0$$

$$\frac{\partial U}{\partial T}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}+\frac{\partial P}{\partial X}-\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right)=0$$

$$\frac{\partial V}{\partial T}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}+\frac{\partial P}{\partial X}-\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right)=0$$

$$\frac{\partial W}{\partial T}+U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}+\frac{\partial P}{\partial X}-\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right)=0$$

EXPERIMENTAL DATA LOSS

$$\left\|\vec{V}-\vec{V}\right\|^2=0$$

Figure. 17. Physics-based neural network for solving the Navier-Stokes equation. where blue circles on the left indicate inputs, blue circles on the right indicate outputs, and yellow circles indicate end-to-end. The input values X, Y, and Z are spatial coordinates and T is time, while the output values U, V, and W are the velocities of the flow field and P is the pressure.

6 Conclusions

6.1 Challenges and limitations hybrid aquatic-aerial vehicle

Summarizing the above, it can be concluded that the current challenges and limitations faced by biomimetic vehicles, constructed on the basis of biological models, are primarily due to the lack of a suitable energy system, the complexity of collecting and processing biological data, the difficulty of developing biomimetic vehicles, and the limited range of applications. The following provides a specific analysis of these challenges and limitations.

6. 1. 1Data problem

Biological Data Collection Problems

(1) High-speed motion capture involves the study of fast-moving creatures such as birds, insects, and fish. This necessitates the use of high-speed camera equipment or other precise measurement techniques to capture and record their flight paths. However, high-speed equipment is costly and complex to operate, and its performance can be affected by factors such as ambient light and background noise.

(2) Size challenge: Organisms and their structures vary in size, requiring different equipment for collecting data on them. The need to use various collection devices, combined with the complexity of the objects to be analyzed, makes accurate data collection challenging.

(3) Behavioral complexity: The movement behavior of living things is very complex, including a variety of actions such as taking off, hovering, steering, and landing. These actions involve the coordination of multiple muscles and nervous systems, making the accurate measurement and interpretation of biological motor behavior difficult.

(4) Environmental interference: The motor behavior of organisms is influenced by a variety of environmental factors, including temperature, humidity, wind speed, air pressure, and flow velocity, among others. These factors can introduce fluctuations and uncertainties in the data. To obtain reliable data, it is essential to control experimental conditions and conduct repeated experiments.

(5) Variety of data: Biological movement data that need to be collected are highly varied, including the beat frequency of wings or fins, the speed, and the acceleration of the movement, among other types. These data must be collected simultaneously as the creature performs the movement, with each data point accurately matched with the corresponding motion. This process increases the workload and complexity of the data collection task.

Biological Data processing problems

(1) Complexity of Data Interpretation: The motion data of organisms contain a large amount of information, such as movement trajectory, velocity, acceleration, and change of direction. Interpreting these data requires a deep background in biology, physics, and mathematics, as well as an in-depth understanding of behaviors such as swimming, flying, and gliding.

(2) Interference from other data: Collected biological data are typically multidimensional, noisy, and encompass a large number of samples and variables. This characteristic makes data processing and analysis both complex and time-consuming. To extract useful information and patterns, specialized statistical methods and computational tools are required.

(3) Difficulties in data integration and sharing: Data on biological movements typically originate from various research teams and laboratories. Data formats and collection methods can vary, leading to challenges in data integration and sharing. This variability limits the effectiveness of data utilization and can constrain the depth of research.

(4) Difficulty in data utilization: Aspects such as the structure, skeleton, and flesh in living organisms differ greatly from the mechanical bodies of navigational vehicles. Typically, data collected from living organisms cannot be directly applied to the design and motion of navigational vehicles, necessitating some modifications. However, the vastly different composition and structure make it extremely challenging to modify the collected data on an organism's motion and apply it to the navigator.

6. 1. 2 Vehicle data problems

Similar to the collection and processing of biological data, bionic vehicles are characterized by high speed, complex structures, various forms of motion, and a wide range of data to be collected. The data can be affected by environmental factors and other challenges. The process of improving the bionic vehicle through experimental data also presents a data-related challenge.

6. 1. 3 Challenges in designing bionic vehicles

(1) Difficulty of technical realization: Bionic navigators need to mimic the locomotion mechanisms of living creatures, which requires an in-depth understanding of biological motion and the mechanisms by which it can be transformed into mechanical motion. This involves many aspects, such as complex mechanical design, material selection, and power system design, making the realization of this technology challenging.

(2) Complexity of biological mechanism: The mechanism of biological movement is usually very complex, involving the synergistic action of multiple muscles, bones, and nervous systems. To accurately simulate these mechanisms, in-depth knowledge of biological kinematics, dynamics, and physiology is required, demanding a high level of expertise from researchers.

(3) Challenges of environmental adaptability: Bionic vehicles must operate in diverse environments, both underwater and aerial. These environments impose unique performance, material, and power system specifications on the navigator. Maintaining the navigator's stability and performance across various environments presents a significant challenge.

6. 1. 4 Challenges of model control

(1) Computational burden: MPC requires solving an optimization problem online, which is computationally intensive, especially when the model is large or has many constraints.

(2) Model Accuracy: The performance of MPC depends on the accuracy of the model. If the model deviates significantly from the actual system, the control effect will be affected.

(3) Robustness: in practical applications, the system may be subject to various uncertainties and external disturbances, which require the design of robust MPC algorithms.

6. 1. 5 Limitations of the localization system

(1) computational complexity: SLAM algorithms usually need to process a large amount of data and have high real-time requirements, which challenges computational resources.

(2) Environmental changes: Dynamic or changing environments may cause SLAM systems to fail.

(3) Sensor errors: Sensor inaccuracies and noise can affect the accuracy of SLAM.

(4) initialization and robustness: SLAM systems require an effective initialization process and remain robust in the face of sensor failures or extreme conditions.

6. 1. 6 Challenges and limitations of Battery Management System

(1) Safety: Battery failure may lead to fire or explosion, so the safety of BMS is crucial.

(2) Reliability: The BMS must be able to work stably for a long time under various environmental conditions.

(3) Accuracy: Accurate power calculation and state estimation are critical to user and system functionality.

(4) Cost: While ensuring performance, the cost of the BMS needs to be controlled to suit the needs of different applications.

6. 1. 7 Appearance design issues

(1) Mesh quality: The accuracy of finite element analysis relies heavily on the quality of the mesh. A poor mesh may lead to wrong results.

(2) Computational resources: For large-scale and complex problems, finite element analysis requires a large amount of computational resources.

(3) Model validation: The reliability of FEA models needs to be verified by experimental data.

(4) User experience: The results of FEA are influenced by the user's understanding of physical phenomena, model selection and parameter settings.

6. 2 Suggestions and prospects

6. 2.1 Suggestions Optimizing Data Collection

(1) Based on the different measurement objects, environments, and required data, experimental equipment and measuring instruments can be used in a scientific manner, and measurement methods and paths can be designed in a logical and effective way.

(2) Improve the precision of measurement when collecting data to ensure the accuracy and reliability of experimental data.

(3) Integrate with other fields, such as collaborating with research groups in biological research. Exchange data with these groups to obtain the additional data needed.

(4) Analyze the data collected in different environments to extract common features and similar patterns, and identify the useful data within.

(5) Divide the motion of organisms into distinct segments and collect data for each segment independently. Extract the experimental data from each segment for analysis, ensuring that the influence of one segment on another is minimized. This approach will improve the accuracy of data collection for the study of individual movements.

(6) While collecting data from one section of the organism's motions, gather multiple sets of data from that motion independently. For example, the frequency of fin or wing beats should be collected as a single dataset. Each set of data is then analyzed and studied. The movement data collected separately but simultaneously and under the same conditions are subsequently combined. This combined data is then analyzed and compared with the overall dataset to identify trends and patterns.

6. 2. 2 Data Processing Optimization Suggestions

(1) Decompose complex motion data into its constituent elements, such as motion trajectory, velocity, and acceleration. Then, analyze these datasets from different disciplinary perspectives.

(2) Research and develop artificial intelligence techniques and algorithms for bionic vehicles and biokinetics. Explore the numerical relationships between biokinematics and bionic vehicles, and enhance the accuracy and reliability in transforming the data.

(3) Apply the obtained bio kinematic data to vehicles of varying sizes to determine the most suitable bio kinematic data for a biomimetic vehicle. This approach can enhance the vehicle's performance.

(4) The data can be analyzed in depth using methods such as statistical analysis and multi-scale analysis. For example, richer structural information can be extracted by processing the gradient and mean values of the data.

6. 2. 3 Suggestions for bionic vehicle design

(1) In-depth understanding of biological movement mechanism: When designing a bionic navigator, it is first necessary to have an in-depth understanding of the movement mechanism of the simulated organisms. This includes aspects such as the mode of movement, muscle and bone structure, and nervous system control. A deep understanding of these mechanisms can provide a strong basis for the design of the bionic vehicle.

(2) Choose appropriate propulsion mode: The propulsion mode of the bionic vehicle can be borrowed from that of living creatures, such as propeller propulsion and bionic pectoral fin propulsion. According to the use environment and performance requirements of the bionic vehicle, the appropriate propulsion method should be chosen. At the same time, it may be beneficial to consider combining multiple propulsion methods to enhance the maneuverability and efficiency of the vehicle.

(3) Optimize mechanical structure and material selection: In the design of bionic vehicles, the selection of mechanical structure and materials is crucial. The design should include a mechanical structure and material selection tailored to the movement mechanism and propulsion method of the simulated organism. At the same time, factors such as the weight, strength, and durability of the vehicle should be considered to ensure its performance and service life.

(4) Develop advanced control system: The control system of the bionic navigator is key to realizing its motion and function. It is necessary to develop an advanced control system to achieve precise control over the vehicle's motion parameters, such as thrust, steering, and speed. At the same time, the stability and safety of the navigator must be ensured for reliable operation across various environments.

(5) The bionic vehicle must operate in various environments, including underwater and in the air. When designing, it is crucial to prioritize environmental adaptability and consider the navigator's performance across different settings. For instance, in underwater environments, the vehicle's waterproofing and corrosion resistance must be taken into account. Similarly, in aerial environments, the vehicle's aerodynamic resistance and stability are key considerations.

6. 2. 4 Suggestions for Control algorithms

(1) Algorithm optimization: research more efficient optimization algorithms to reduce computation time.

(2) Online modeling: incorporating a data-driven approach for online updating and self-adaptation of models.

(3) Distributed MPC: For large-scale systems, research on distributed MPC

6. 2. 5 Navigation and localization algorithms Suggestions

(1) Multi-sensor fusion: combining multiple sensors (e.g., laser, vision, IMU) to improve the accuracy and robustness of SLAM.

(2) Deep Learning: Use deep learning techniques to improve feature extraction, data association and map representation.

(3) Embedded and mobile platforms: develop SLAM algorithms for resource-constrained embedded systems and mobile platforms.

(4) Large-scale and indoor SLAM: Addressing localization and map building problems in large-scale environments, as well as challenges in indoor environments such as lack of features and dynamic changes.

6. 2. 6 Suggestions for Battery Management System

(1) Intelligent: Use advanced algorithms and artificial intelligence technology to improve the accuracy of state estimation and the intelligence level of the system.

(2) Integration: Integrate more functions into the BMS to reduce volume and cost.

(3) Standardization: Promote the standardization of BMS to facilitate compatibility between batteries and systems from different manufacturers.

(4) Wireless communication: Adopt wireless communication technology to simplify the design and maintenance of battery system.

6. 2. 7 Appearance design Suggestions

(1) Automated mesh generation: develop efficient mesh generation techniques to adapt to complex geometries and automatically adjust mesh density.

(2) Adaptive Finite Element Methods (AFEM): Automatically adjust the mesh according to the error estimation of the solution in order to improve the efficiency and accuracy of the solution.

(3) Multi-physical field coupling: the development of finite element technology that can simultaneously simulate multiple physical field coupling problems.

(4) High-performance computing: Utilize high-performance computing resources to deal with larger scale and more complex finite element problems.

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References:

1. Bai L, Guvenc I, Yu Q, Zhang WJIIoTJ. Guest editorial special issue on unmanned aerial vehicles over Internet of Things. 2019; 6: 1636-1639

2. Crawford A, Shore J, Shan SJIJoOE. Measurement of tidal currents using an autonomous underwater vehicle. 2021; 47: 282-294

3. Li H, Wu X, Zhang Z, Tan X, Pan Y, Dai C, Luo D, Ahmed A, Xu YJI. An extended-range wave-powered autonomous underwater vehicle applied to underwater wireless sensor networks. 2022; 25

4. Danckaers A, Seto MLJAR. Transmission of images by unmanned underwater vehicles. 2020; 44: 3-24

5. Yang L, Zhao S, Wang X, Shen P, Zhang TJJoMS, Engineering. Deep-Sea underwater cooperative operation of manned/unmanned submersible and surface vehicles for different application scenarios. 2022; 10: 909

6. Chen Y, Wang H, Helbling EF, Jafferis NT, Zufferey R, Ong A, Ma K, Gravish N, Chirarattananon P, Kovac MJSr. A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. 2017; 2: eaao5619

7. Mercado D, Maia M, Diez FJJJoI, Systems R. Aerial-underwater systems, a new paradigm in unmanned vehicles. 2019; 95: 229-238

8. Sun Y, Liu X, Cao K, Shen H, Li Q, Chen G, Xu J, Ji AJJoBE. Design and Theoretical Research on Aerial-Aquatic Vehicles: A Review. 2023; 20: 2512-2541

9. Petrov GJJof. Flying submarine. 1995

10. Crouse G. Conceptual design of a submersible airplane. 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition; 2010. p. 1012.

11. Schemensky RTJC. Convair Aerospace Division b. GROUP. 1973; 223: 1

12. Yao G, Li Y, Zhang H, Jiang Y, Wang T, Sun F, Yang XJPiAS. Review of hybrid aquatic-aerial vehicle (HAAV): Classifications, current status, applications, challenges and technology perspectives. 2023; 139: 100902

13. Reid BD. The Flying Submarine: The Story of the Invention of the Reid Flying Submarine, RFS-1. Heritage Books; 2012.

14. Henkel J. Exploring the Potential use of Long-Range Unmanned Aerial Systems to Address Capability Gaps in the United States Coast Guard. Acquisition Research Program; 2023.

15. Yang X, Wang T, Liang J, Yao G, Liu MJPiAS. Survey on the novel hybrid aquatic–aerial amphibious aircraft: Aquatic unmanned aerial vehicle (AquaUAV). 2015; 74: 131-151

16. Tan YH, Chen BMJUS. Survey on the development of aerial–aquatic hybrid vehicles. 2021; 9: 263-282

17. Stewart W, Weisler W, MacLeod M, Powers T, Defreitas A, Gritter R, Anderson M, Peters K, Gopalarathnam A, Bryant MJB, biomimetics. Design and demonstration of a seabird-inspired fixed-wing hybrid UAV-UUV system. 2018; 13: 056013
18. Bershadsky D, Haviland S, Valdez PE, Johnson E. Design considerations of submersible unmanned flying vehicle for communications and underwater sampling. OCEANS 2016 MTS/IEEE Monterey: IEEE; 2016. p. 1-8.
19. Yang FL, Wang YQJAM. Effect of thoracic muscle on dynamic performance of flexible flapping wings of insects. 2024; 235: 597-613
20. Roper D, Sharma S, Sutton R, Culverhouse PJPotIoME, Part M: Journal of Engineering for the Maritime Environment. A review of developments towards biologically inspired propulsion systems for autonomous underwater vehicles. 2011; 225: 77-96
21. Wells D. 100 birds and how they got their names. Algonquin Books; 2001.
22. Bhar K, Chang B, Virot E, Straker L, Kang H, Paris R, Clanet C, Jung SJJotRSI. How localized force spreads on elastic contour feathers. 2019; 16: 20190267
23. Bonser RHJI. The elastic properties of wing and contour feather keratin from the Ostrich Struthio camelus. 2001; 143: 144-145
24. Daoust P, Dobbin G, RCF RA, Dawson SJS. Descriptive anatomy of the subcutaneous air diverticula in the Northern Gannet Morus bassanus. 2008; 21: 64-76
25. Tully TN, Dorrestein GM, Jones AK. Handbook of avian medicine. 2009
26. Liang J, Yao G, Wang T, Yang X, Zhao W, Song G, Zhang YJSCTS. Wing load investigation of the plunge-diving locomotion of a gannet Morus inspired submersible aircraft. 2014; 57: 390-402
27. Schreiber R. The Sulidae: Gannets and Boobies. JSTOR; 1979.
28. Yang X, Wang T, Liang J, Yao G, Zhao W. Submersible unmanned aerial vehicle concept design study. 2013 Aviation Technology, Integration, and Operations Conference; 2013. p. 4422.
29. Wang T, Yang X, Liang J, Yao G, Zhao WJB, biomimetics. CFD based investigation on the impact acceleration when a gannet impacts with water during plunge diving. 2013; 8: 036006
30. Ropert-Coudert Y, Grémillet D, Ryan P, Kato A, Naito Y, Le Maho YJI. Between air and water: the plunge dive of the Cape Gannet Morus capensis. 2004; 146: 281-290
31. Zheng Y, Huang Z, Zhang C, Wu ZJAS. Hydrophobic antiwetting of aquatic UAVs: static and dynamic experiment and simulation. 2022; 12: 7626
32. Yang W, Wang L, Song BJIJoMAV. Dove: A biomimetic flapping-wing micro air vehicle. 2018; 10: 70-84

33. Zufferey R, Ancel AO, Farinha A, Siddall R, Armanini SF, Nasr M, Brahmal R, Kennedy G, Kovac MJSR. Consecutive aquatic jump-gliding with water-reactive fuel. 2019; 4: eaax7330
34. Lasek M, Pietrucha J, Sibilski K, Zlocka M. The comparative evaluation of power requirements for fixed, rotary and flapping wings micro air vehicles. 25th Congress of the International Council of the Aeronautical Sciences; 2006.
35. Earls KDJJoEB. Kinematics and mechanics of ground take-off in the starling Sturnis vulgaris and the quail Coturnix coturnix. 2000; 203: 725-739
36. Huang J, Wang T, Lueth TC, Liang J, Yang XJIA. CFD based investigation on the hydroplaning mechanism of a cormorant’s webbed foot propulsion. 2020; 8: 31551-31561
37. Yang L-J, Esakki B, Chandrasekhar U, Hung K-C, Cheng C-MJIJoMAV. Practical flapping mechanisms for 20 cm-span micro air vehicles. 2015; 7: 181-202
38. Fang X, Wen Y, Gao Z, Gao K, Luo Q, Peng H, Du RJM. Review of the Flight Control Method of a Bird-like Flapping-Wing Air Vehicle. 2023; 14: 1547
39. Silvestre FJ, Guimarães Neto AB, Bertolin RM, da Silva RGA, Paglione PJJoA. Aircraft control based on flexible aircraft dynamics. 2017; 54: 262-271
40. Siddall R, Ortega Ancel A, Kovač MJIf. Wind and water tunnel testing of a morphing aquatic micro air vehicle. 2017; 7: 20160085
41. O'Dor R, Stewart J, Gilly W, Payne J, Borges TC, Thys TJDSRPITSiO. Squid rocket science: how squid launch into air. 2013; 95: 113-118
42. Vogel SJTBB. Flow-assisted mantle cavity refilling in jetting squid. 1987; 172: 61-68
43. Yu J, Su Z, Wu Z, Tan MJIAToM. Development of a fast-swimming dolphin robot capable of leaping. 2016; 21: 2307-2316
44. Yu J, Wu Z, Su Z, Wang T, Qi SJIAToM. Motion control strategies for a repetitive leaping robotic dolphin. 2019; 24: 913-923
45. Yu J, Su Z, Wang M, Tan M, Zhang JJITor. Control of yaw and pitch maneuvers of a multilink dolphin robot. 2011; 28: 318-329
46. Wang Y-L, Tai C-H, Huang H-RJJoME, Technology. Design and development of an autonomous underwater vehicle–robot dolphin. 2015; 14: 44-55
47. Siddall R, Kovač MJB, biomimetics. Launching the AquaMAV: bioinspired design for aerial–aquatic robotic platforms. 2014; 9: 031001
48. Davenport JJRiFB, Fisheries. How and why do flying fish fly? 1994; 4: 184-214
49. Park H, Choi HJJoEB. Aerodynamic characteristics of flying fish in gliding flight. 2010; 213: 3269-3279

50. Gao A, Techet AH. Design considerations for a robotic flying fish. OCEANS'11 MTS/IEEE KONA: IEEE; 2011. p. 1-8.
51. Ma KY, Chirarattananon P, Fuller SB, Wood RJJS. Controlled flight of a biologically inspired, insect-scale robot. 2013; 340: 603-607
52. Chen Y, Helbling EF, Gravish N, Ma K, Wood RJ. Hybrid aerial and aquatic locomotion in an at-scale robotic insect. 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): IEEE; 2015. p. 331-338.
53. Horn AC, Pinheiro PM, Silva CB, Neto AA, Drews-Jr PL. A study on configuration of propellers for multirotor-like hybrid aerial-aquatic vehicles. 2019 19th International Conference on Advanced Robotics (ICAR): IEEE; 2019. p. 173-178.
54. Alzu'bi H, Mansour I, Rawashdeh OJJofR. Loon copter: Implementation of a hybrid unmanned aquatic–aerial quadcopter with active buoyancy control. 2018; 35: 764-778
55. Maia MM, Soni P, Diez FJJapa. Demonstration of an aerial and submersible vehicle capable of flight and underwater navigation with seamless air-water transition. 2015
56. Maia MM, Mercado DA, Diez FJ. Design and implementation of multirotor aerial-underwater vehicles with experimental results. 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): IEEE; 2017. p. 961-966.
57. Young T. Design and testing of an air-deployed unmanned underwater vehicle. 14th AIAA Aviation Technology, Integration, and Operations Conference; 2014. p. 2721.
58. Chen Y, Wang G, Xu G, Zhang W, Wang WJIJoARS. Hovering control of submarine based on L1 adaptive theory via ballast tanks. 2017; 14: 1729881417724191
59. Weisler W, Stewart W, Anderson MB, Peters KJ, Gopalarathnam A, Bryant MJIJoOE. Testing and characterization of a fixed wing cross-domain unmanned vehicle operating in aerial and underwater environments. 2017; 43: 969-982
60. Gao T, Lin Y, Ren HJOE. The role studies of fixed-wings in underwater fan-wing thrusters. 2020; 216: 108049
61. Lu D, Xiong C, Lyu B, Zeng Z, Lian L. Multi-mode hybrid aerial underwater vehicle with extended endurance. 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans (OTO): IEEE; 2018. p. 1-7.
62. Lu D, Xiong C, Zhou H, Lyu C, Hu R, Yu C, Zeng Z, Lian LJOE. Design, fabrication, and characterization of a multimodal hybrid aerial underwater vehicle. 2021; 219: 108324
63. Lu D, Xiong C, Zeng Z, Lian L. A multimodal aerial underwater vehicle with extended endurance and capabilities. 2019 International Conference on Robotics and Automation (ICRA): IEEE; 2019. p. 4674-4680.

64. Liang X, Liu C, Zeng ZJM. Multi-domain informative coverage path planning for a hybrid aerial underwater vehicle in dynamic environments. 2021; 9: 278
65. Chen X, Bai YK, Zhao CZ, Shen X, Zhang QJAC. Lithium bonds in lithium batteries. 2020; 132: 11288-11291
66. Wang P, Tian X, Lu W, Hu Z, Luo YJAMM. Dynamic modeling and simulations of the wave glider. 2019; 66: 77-96
67. Tian D, Zhang H, Wang S, Zhang W, Sun X, Zhou Y, Zheng G, Jiang H, Yang S, Zhou FJJoGRA. Sea surface wind structure in the outer region of tropical cyclones observed by wave gliders. 2023; 128: e2022JD037235
68. Zhang Y, Rueda C, Kieft B, Ryan JP, Wahl C, O’Reilly TC, Maughan T, Chavez FPJJoFR. Autonomous tracking of an oceanic thermal front by a Wave Glider. 2019; 36: 940-954
69. Iinuma T, Kido M, Ohta Y, Fukuda T, Tomita F, Ueki IJFiES. GNSS-Acoustic observations of seafloor crustal deformation using a wave glider. 2021; 9: 600946
70. Wang L, Li Y, Liao Y, Pan K, Zhang WJIToIE. Course control of unmanned wave glider with heading information fusion. 2018; 66: 7997-8007
71. Wang P, Zhang X, Wang D, Guo X, Lu W, Tian XJAOR. A restricted circle based position keeping strategy for the wave glider. 2020; 97: 102081
72. Liu F, Lan T, Wei Z, Sun X, Zhang S, Sang H, Huang FJOE. Adaptive propeller rudder controller for the wave glider with a propeller-rudder control system. 2023; 289: 116129
73. Sun X, Ma S, Sang H, Li C, Liu JJOE. Research on the propulsion performance of spring-hydrofoil mechanism of the wave glider. 2022; 266: 112709
74. Lyu Z, Ding W, Sun X, Sang H, Zhou Y, Yu P, Zheng LJJoMS, Engineering. Dynamic landing Control of a Quadrotor on the Wave Glider. 2021; 9: 1119
75. Tian D, Zhang H, Zhang W, Zhou F, Sun X, Zhou Y, Ke DJW. Wave glider observations of surface waves during three tropical cyclones in the South China Sea. 2020; 12: 1331
76. Li Y, Ma ZJOE. Numerical investigation on novel conceptual design of hybrid-driven autonomous underwater glider with active twin flapping foils. 2020; 214: 107867
77. Ore JP, Elbaum S, Burgin A, Detweiler CJJoFR. Autonomous aerial water sampling. 2015; 32: 1095-1113
78. Lopez-Tello P, Fernandez-Feria RJPRF. Effect of flexibility on the self-propelled locomotion by an elastically supported stiff foil actuated by a torque. 2023; 8: 063102
79. Licht S, Polidoro V, Flores M, Hover FS, Triantafyllou MSJIJooe. Design and projected performance of a flapping foil AUV. 2004; 29: 786-794

80. Zhang M, Liu X, Chu D, Guo S. The principle of turtle motion and bio-mechanism of its four limbs research. 2008 IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application: IEEE; 2008. p. 573-578.
81. McGill R, Hyun N-sP, Wood RJJIR, Letters A. Frequency-Modulated Control for Insect-Scale Flapping-Wing Vehicles. 2022; 7: 12515-12522
82. Shimura K, Aono H, Kang C-kJJoBE. An Experimental Study on Response and Control of a Flapping-Wing Aerial Robot Under Wind Gusts. 2024; 21: 209-223
83. Koh J-S, Yang E, Jung G-P, Jung S-P, Son JH, Lee S-I, Jablonski PG, Wood RJ, Kim H-Y, Cho K-JJS. Jumping on water: Surface tension–dominated jumping of water striders and robotic insects. 2015; 349: 517-521
84. Hu DL, Chan B, Bush JWJn. The hydrodynamics of water strider locomotion. 2003; 424: 663-666
85. Korde UAJOE. Study of a jet-propulsion method for an underwater vehicle. 2004; 31: 1205-1218
86. Mardanpour P, Izadpanahi E, Powell S, Rastkar S, Bejan AJJotb. Inflected wings in flight: Uniform flow of stresses makes strong and light wings for stable flight. 2021; 508: 110452
87. Benotsmane R, Vásárhelyi JJE. Towards optimization of energy consumption of tello quad-rotor with mpc model implementation. 2022; 15: 9207
88. Xue R, Dai L, Wang P, Sun Z, Xia YJICT, Applications. Output feedback stochastic MPC for tracking control of quadrotors with disturbances. 2024; 18: 566-580
89. Han Y, Du X, Wei Y, Sun J, Li YJOE. Nonlinear model predictive control of supercavitating vehicle based on memory effect. 2024; 299: 117302
90. Gupta PM, Pairet E, Nascimento T, Saska MJIR, Letters A. Landing a UAV in harsh winds and turbulent open waters. 2022; 8: 744-751
91. Nascimento T, Saska MJJoI, Systems R. Embedded fast nonlinear model predictive control for micro aerial vehicles. 2021; 103: 1-11
92. Ma TJA. Filtering adaptive tracking controller for multivariable nonlinear systems subject to constraints using online optimization method. 2020; 113: 108689
93. Ma H, Zhang Y, Wang S-Q, Xu J, Su HJOE. Rolling-optimized model predictive vibration controller for offshore platforms subjected to random waves and winds under uncertain sensing delay. 2022; 252: 111054
94. Zheng H, Chen W, Xie FJIA. Control Simulation of Flapping-Wing Micro Aerial Vehicle Based on Multi-Level Optimization Model Predictive Control. 2024
95. Hong SH, Ou J, Wang YJNC, Applications. Physics-guided neural network and GPU-accelerated nonlinear model predictive control for quadcopter. 2023; 35: 393-413

96. Zhao M, Lin S, Cao Y, Zhou Z, Shi T, Xia CJIToIE. Explicit model predictive cascade-free direct force and torque control of quadrotors. 2023
97. Zhang B, Wang Y, Yao W, Sun GJISJ. HTSR-VIO: Real-time Line-Based Visual-Inertial Odometry with Point-Line Hybrid Tracking and Structural Regularity. 2024
98. Debeunne C, Vivet DJS. A review of visual-LiDAR fusion based simultaneous localization and mapping. 2020; 20: 2068
99. Munguía R, Urzua S, Bolea Y, Grau AJS. Vision-based SLAM system for unmanned aerial vehicles. 2016; 16: 372
100. Wei W, Zhu X, Wang YJFoIT, Engineering E. Novel robust simultaneous localization and mapping for long-term autonomous robots. 2022; 23: 234-245
101. Wu Y, Kuang J, Niu X, Behley J, Klingbeil L, Kuhlmann HJIR, Letters A. Wheel-SLAM: Simultaneous localization and terrain mapping using one wheel-mounted IMU. 2022; 8: 280-287
102. Hashim HA, Eltoukhy AEJIToS, Man,, Systems C. Nonlinear filter for simultaneous localization and mapping on a matrix lie group using imu and feature measurements. 2021; 52: 2098-2109
103. Xu Y, Wan D, Bi S, Guo H, Zhuang YJSN. A FIR filter assisted with the predictive model and ELM integrated for UWB-based quadrotor aircraft localization. 2023; 4: 2
104. Sierra G, Orchard M, Goebel K, Kulkarni CJRE, Safety S. Battery health management for small-size rotary-wing electric unmanned aerial vehicles: An efficient approach for constrained computing platforms. 2019; 182: 166-178
105. Shibl MM, Ismail LS, Massoud AMJJoES. A machine learning-based battery management system for state-of-charge prediction and state-of-health estimation for unmanned aerial vehicles. 2023; 66: 107380
106. Viviani A, Aprovitola A, Iuspa L, Pezzella GJAS, Technology. Aeroshape design of reusable re-entry vehicles by multidisciplinary optimization and computational fluid dynamics. 2020; 105: 106029
107. Rayner JMJE. Pleuston: animals which move in water and air. 1986; 10: 58-64
108. Sigrest P, Wu N, Inman DJJB, Biomimetics. Energy considerations and flow fields over whiffling-inspired wings. 2023; 18: 046007
109. Li J, Zhang X, Zhou J, Dong X, Zhang C, Ji ZJAS. swHPFM: Refactoring and optimizing the structured grid fluid mechanical algorithm on the sunway taihulight supercomputer. 2019; 10: 72
110. Chedevergne FJJoT. Modeling rough walls from surface topography to double averaged Navier-Stokes computation. 2023; 24: 36-56

111. Brunton SL, Noack BR, Koumoutsakos PJArofm. Machine learning for fluid mechanics. 2020; 52: 477-508
112. Tao M. Kinetic Equation Study on Momentum Conservation of Aerodynamics Incompressible Fluid of High-Altitude Aircraft. Journal of Physics: Conference Series: IOP Publishing; 2023. p. 012015.
113. Wu X, Wu Z, Liang L, Zhao J, Wang W, Yan SJAS, Technology. Bio-inspired design and performance evaluation of a novel morphing nose cone for aerospace vehicles. 2023; 137: 108274
114. Liu B, Pang J, Tu X, Zhou ZJM. Three components strain-gauge type aircraft surface friction resistance sensor: Design, manufacturing, and calibration. 2023; 218: 113165