Current Status and Prospect of Aquatic-aerial Unmanned Vehicles

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Abstract. As people have higher and higher requirements for water-air detection and communication, the research of aquatic-aerial unmanned vehicles with high flexibility and maneuverability has become more and more in-depth. In this paper, the aquatic-aerial unmanned vehicles is classified according to their driving modes and constructions, and the aquatic-aerial unmanned vehicles is divided into multi-rotor vehicles, fixed-wing vehicles and bionic principle driven vehicles. This paper will give the readers a detailed and comprehensive introduction to the aquatic-aerial unmanned vehicles. In this paper, the aquatic-aerial unmanned vehicles is classified according to their driving modes and constructions, and the aquatic-aerial unmanned vehicles is divided into multi-rotor vehicles, fixed-wing vehicles and bionic principle driven vehicles, and the driving principle and operation mode of each type of aquatic-aerial unmanned vehicles are introduced. At the same time, the application of aquatic-aerial unmanned vehicles in different scenarios is analyzed, so that readers can have some reference when they need to buy or develop aquatic-aerial unmanned vehicles.

Keywords: Aquatic-aerial Unmanned Vehicles List the; Multi-rotor; Fixed-wing; Bionic principle.

1. Introduction

Due to the complex and dangerous underwater conditions, many underwater tasks need to be completed by robots instead of humans, such as exploration, rescue and inspection of offshore equipment [1]. However, most unmanned underwater vehicle (UUVs) need to sail from their location to the designated location by itself, or need to be transported by boat to get to the designated location and finish its works. Autonomous navigation to the destination may cause the robot to use more power on the road due to battery life problems, resulting in insufficient time to perform the task. And the method of shipping will cost a lot of unnecessary manpower and resources. So scientists have developed various forms of vehicles to solve these problems and perform certain tasks better [2]. Aquatic-aerial unmanned vehicles is one of the special and novel ones. Through trans-medium navigation, aquatic-aerial unmanned vehicles can complete more possible tasks than ordinary underwater robot. The aquatic-aerial unmanned vehicles can fly fast and flexibly like a drone in the air, without the need to sail in the environment of high water resistance all the time [3].

This paper will give the readers a detailed and comprehensive introduction to the aquatic-aerial unmanned vehicles. In this paper, the aquatic-aerial unmanned vehicles is classified according to their driving modes and constructions, and the aquatic-aerial unmanned vehicles is divided into multi-rotor vehicles, fixed-wing vehicles and bionic principle driven vehicles, and the driving principle and operation mode of each type of aquatic-aerial unmanned vehicles are introduced. At the same time, the application of aquatic-aerial unmanned vehicles in different scenarios is analyzed, so that readers can have some reference when they need to buy or develop aquatic-aerial unmanned vehicles. This paper also introduces the key technologies of developing and design aquatic-aerial unmanned vehicles. The technical difficulties and current applications of aquatic-aerial unmanned vehicles are also analyzed.

2. Current Development Situation

According to the propulsion mode, the current aquatic-aerial unmanned vehicles can be divided into three categories: multi-rotor vehicles, fixed-wing vehicles and bionic principle driven vehicles. This section will introduce these four types of aquatic-aerial unmanned vehicles respectively [4].

2.1. Multi-rotor Vehicles

Most of the existing aquatic-aerial unmanned vehicles using rotor propulsion are using four or six rotor wings to achieve their navigation in water and air. When in the air, its flight principle is similar to the motion principle of multi-rotor unmanned aerial vehicles (UAVs). The vehicle can hover, flip, advance and retreat through the resultant force generated by its own gravity and lift provided by the rotors.

In 2014 Drews-Jr et al. [1] designed a Hybrid Unmanned Aerial Underwater Vehicle (HUAUV), the model is design based on a quadrotor UAV. And with the addition of an underwater power system, it could navigate underwater. In their paper they analyzed the kinematic and dynamic models. They also estimated and simulated the parameters for a small dimension prototype. The HUAUV uses two sets of propellers, four Aerial propellers on the top and four aquatic propellers below. This design allows the vehicle to easily traverse the medium.

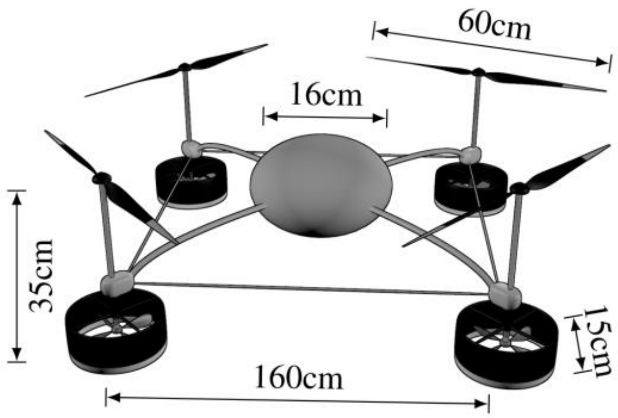

Fig 1. A design of HUAUV proposed by Drews-Jr.

In 2017 Zongcheng Ma et al. [2] designed a hybrid unmanned aerial underwater vehicles (HUAUV). The HUAUV has a group of aerial propellers on the top and a group of underwater propellers below which is similar to the Drews-Jr's design. Based on the Lyapunov stability theory and adaptive sliding mode dynamic surface control, they also designed a depth and attitude controller. In their paper they drew two figures to explain how the HUAUV enter and exit the water which is shown in Fig.3 and Fig.4

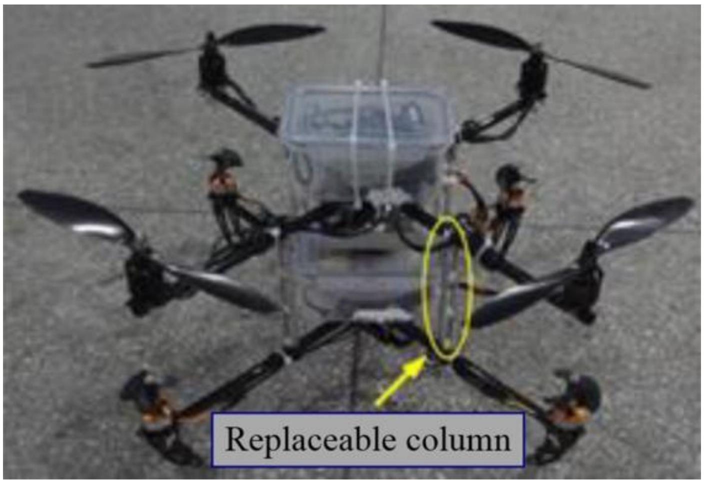

Fig 2. A HUAUV designed by Zongcheng Ma.

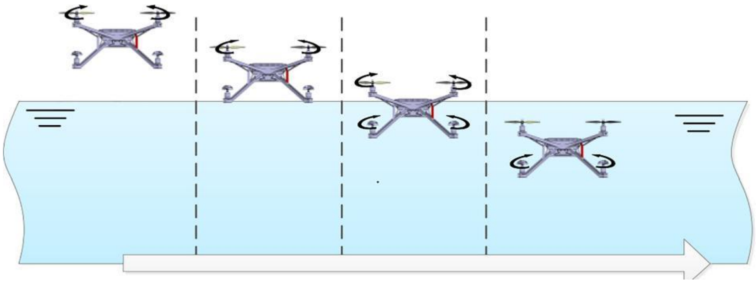

Fig 3. Water entry of the vehicle.

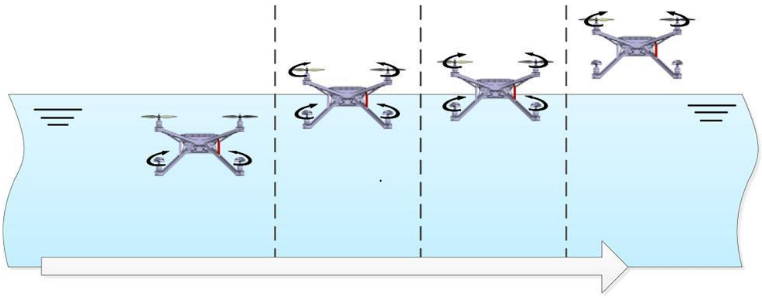

Fig 4. Water exit of the vehicle.

In 2017 D. Mercado [3] developed an air-underwater vehicle with two layers of propellers which are all aerial propellers. This design can avoid the phenomenon which is when one set of propellers are working and another set could do nothing to help but being an encumbrance. That is to say the double-layered propulsion system is fully used when fly in the air, navigate under water or do vertical cross-domain locomotion.

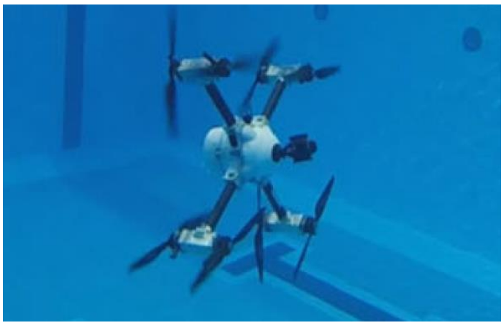

Fig 5. An air-underwater Vehicle designed by D. Mercado.

In 2014, Alzu'bi et al. [4] developed a novel quadcopter that can navigate in both air and water called Loon Copter. The novel design of using only one set of aerial rotors and motors could greatly reduce weight and complexity compared to those designs mentioned above. The version they designed in 2016 used a ballast system to actively control its buoyancy [5]. This system made it possible for the Loon Copter to float on the water surface and go down without the propulsion provided by the propellers.

Fig 6. Loon Copter first 2014 prototype (left) and current 2016 prototype (right).

2.2. Fixed-wing Vehicles

Aquatic-aerial unmanned vehicles with fixed wings can fly in the air at a faster speed and consume less energy, which means that under the same conditions, this kind of aquatic-aerial unmanned vehicles can cross a longer distance at a faster speed in the air to complete a task far from the origin.

In 2017, Robert Siddall et al. [6] developed a unique Aquatic Micro Air Vehicle called AquaMAV. Basically, AquaMAV has a reconfigurable wing, an aerial propeller and motor and a CO_2 powered water jet [7]. AquaMAV's diving strategy was inspired by Sulidae. So when the vehicle needs to dive into the water, the wing will fold up to reduce the resistance when entering. The CO_2 powered water jet is only used when it exit the water. And it works by ejecting water backwards through the pressure of the compressed CO_2.The prototype weighs only 201g and has a flight time of about 14 min, and is expected to be used for data collection or environmental monitoring in specific waters, such as monitoring an offshore oil spill.

Fig 7. AquaMAV.

In 2019, R. Zufferey [8] and his team developed a chemical combustion vehicle. This vehicle is driven by the combustible acetylene gas which is produced by reacting calcium carbide powder with the available environmental water. This kind of water jet can provide a powerful thrust letting the vehicle exit the water at a high speed. However, neither this vehicle nor AquaMAV can take off twice easily because it's a difficulty for them to fill the water tank automatically.

Fig 8. A chemical combustion vehicle.

In 2018, William Stewar et al. [9] developed a fixed-wing unmanned vehicle called EagleRay. The vehicle has the ability to operate in both air and underwater and it can cross domain repeatedly. The vehicle has a passively flooding and draining wing which allows water to flow freely in and out of the wing to reduce excessive buoyancy caused by the relatively large wing cavity in water. EagleRay uses one aerial propeller which is the only source of propulsion when in the air or underwater. And it has successfully complete 12 full-cycle cross-domain missions, whether it is autonomous operation or manually controlled. In the same year, they improved their prototype and analyzed three different designs of crossing between aerial and underwater domains, a quadrotor/fixed-wing hybrid, a vertical takeoff and landing (VTOL) tailsitter aircraft, and a waterjet-assisted takeoff vehicle [10].

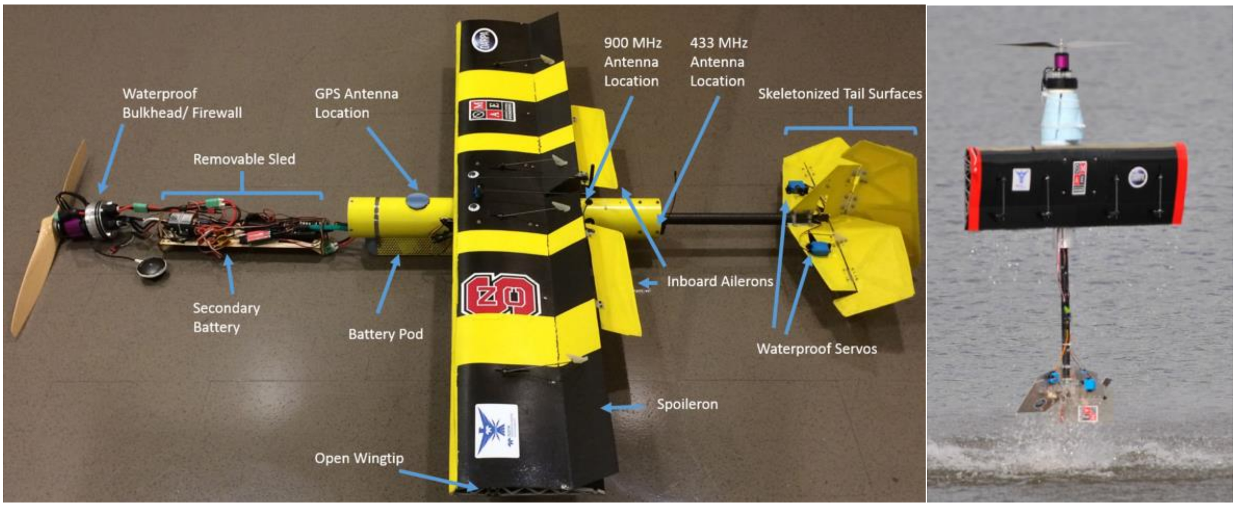

Fig 9. EagleRay (left) and improved EagleRay (right).

In 2021, Zhaoyu Wei et al. [11] designed a fixed-wing unmanned aerial-underwater vehicle (UAUV). The average density of the UAUV is less than that of water. When flying, its fixed-wings provide lift to counteract gravity. The principle is the similar to a normal fixed-wing aircraft. However, in the water the fixed-wings can generate downward force to not let the vehicle be lifted by the large buoyancy. And with the help of the aileron, the vehicle could dive and move smoothly under the water.

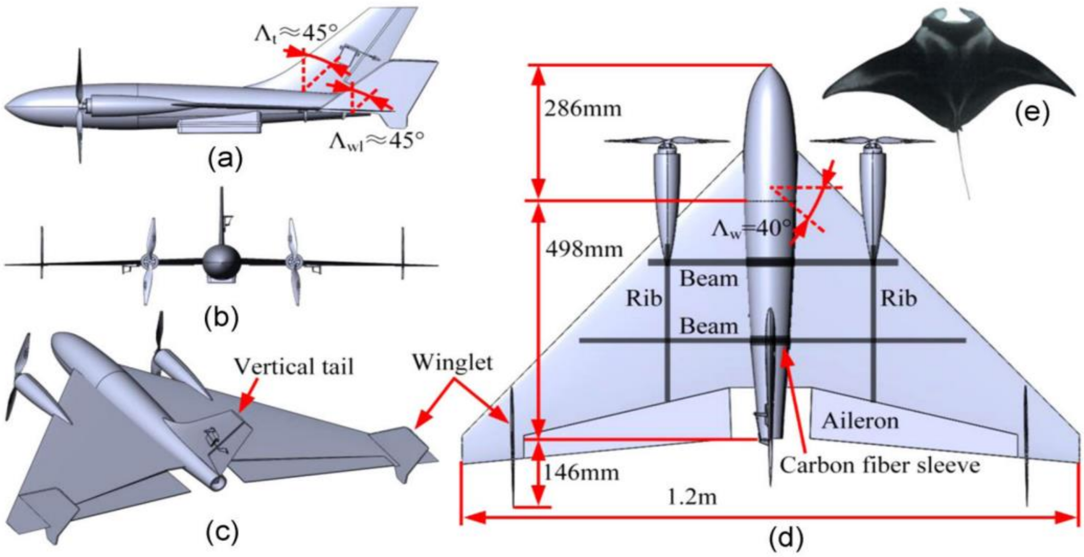

Fig 10. The delta-wing-shaped UAUV.

2.3. Bionic Principle Driven Vehicles

The above-mentioned types of aquatic-aerial unmanned vehicles are powered by propellers while moving in the water and in the air, while the aquatic-aerial unmanned vehicles driven by the principle of bionics are a more novel concept. This kind of robot uses the principle of bionics to realize the drive and attitude control in water and air. However, most of this kind of water-air robot cannot realize long-distance air navigation. Therefore, as aquatic-aerial unmanned vehicles, their application scenarios will be quite different from those of other types.

In 2011, the Department of Mechanical Engineering of Massachusetts Institute of Technology (MIT) developed a prototype of amphibious flying fish [12], and carried out in-depth research on the swimming theory of flying fish, mechanism design and implementation, driving control mode and other aspects, which has certain guiding significance for the future research of bionic prototype.

Fig 11. A prototype of amphibious flying fish.

In 2019, Taogang Hou et al. [13] present a novel prototype of squit robot. The robot has soft fins that can be folded and expanded like natural squid to assist air movement. And it successfully realized underwater movement and water exit by water jet thruster. However, it is not able to sustain air navigation.

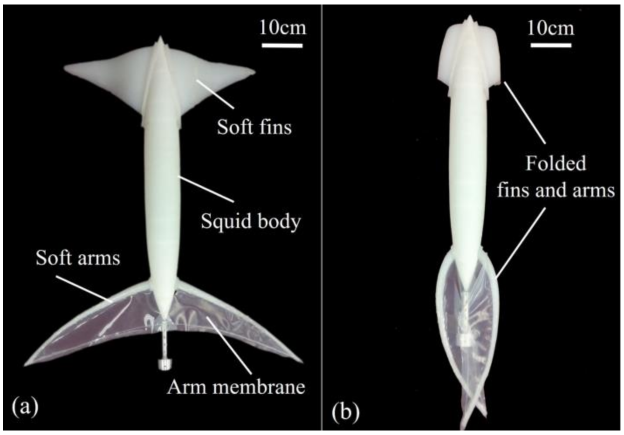

Fig 12. Biomimetic flying squid.

In 2017, Yufeng Chen et al. [14] developed a design of an insect-scale robot weighs only 175-milligram.Although it is fairly small, it has the ability to swim, fly and transition between air and water. Once the robot lands on the water surface, lightweight electrolytic plates will produce oxyhydrogen and buoyancy chamber will collect it to provide enough buoyancy to lift the robot. When the robot needs to take off from the water surface, a sparker will ignites the oxyhydrogen and provide an impulsion to propel the robot.

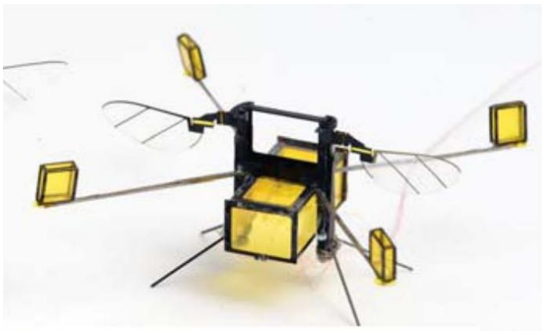

Fig 13. Harvard University bionic insect.

3. Key technologies of aquatic-aerial unmanned vehicles

3.1. The balance of gravity and buoyancy in water

In order to have better underwater performance, most underwater vehicles require the buoyancy to be roughly equal to gravity. So lighter materials or hollow materials are usually used to build the vehicle's frame. Small model airplanes are often made of wood, but given that the vehicles will travel in water, hollow wings or frames made of carbon fiber are a better choice. For example, the chemical combustion vehicle developed by R. Zufferey and the fixed-wings of EagleRay.

Some vehicles are equipped with depth control systems such as water cylinders. These vehicles can easily adjust their self-weight through depth control systems, realize attitude control and altitude control with almost no energy consumption. However, it takes much more energy to control the vehicles' depth in the water through the propeller.

3.2. Water exit and entry of the vehicle

As for the vehicles with rotor propulsion, the problem of water exit and entry has been basically solved. Because when entering the water, the vehicles can arrive the water surface and enter the water at a very slow speed through simple control, and the same is true when exiting the water. The entry mode of vehicles that are similar to seaplanes does not require their construction to have high strength, but they need to slide for a long time and a long distance when entering the water. This kind of vehicles cannot complete the task requiring a precise entry position. So scientists need to figure out how to decrease the damage that may be caused by the relatively high entering speeds. So here comes an entry stance that mimics the behavior of birds when they enter the water to catch fish. The vehicle's depression angle is large, the head enter the water first, at the same the wings would fold. This method can ensure the accuracy of the vehicles' water entry position, and also has higher requirements on the structural strength of the vehicles. For fixed-wing vehicles, here is another way of water exit and entry, which is called vertical takeoff and landing (VTOL). When the vehicle is about to exit the water, it will pitch up to vertical orientation, drain ballast tanks if has them, engage the water and air propellers for egress. When it exit the water, it will disengage the water prop, climb and pitch down to forward flight. When the vehicle is about to enter the water, it will pitch up to vertical hover and gently lower the altitude until it enter the water. Some aircraft also use a backward spray of water to provide the power it needs to get out of the water, which can save energy consumption during the process. But this method is more complicated, each time before water exit it must find a way to fill the container with the right amount of water, or it cannot exit water twice.

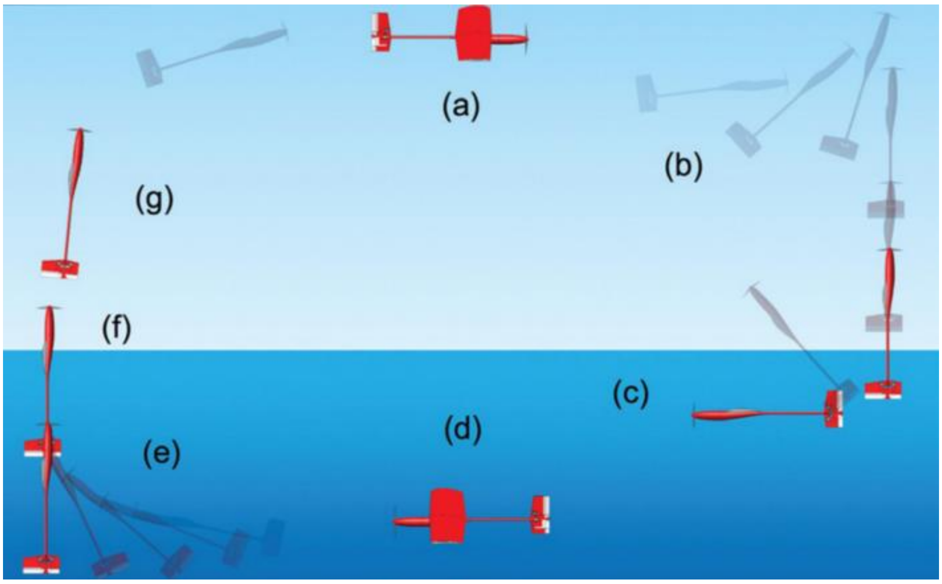

Fig 14. Vertical takeoff and landing (VTOL).

3.3. Energy source

Most long-endurance aircraft use internal combustion engines to provide energy to drive, but the internal combustion engines can't get oxygen during underwater navigation. If the engine needs to operate, it need the oxidant which could only be brought by the vehicle, which is difficult to achieve at present. Therefore, it is generally considered to use electric power to drive the thrusters. So higher energy density batteries could be used to achieve a longer endurance. The energy density of the commonly used lithium battery is very limited. If the lithium battery is used to support a long endurance, the weight, shape and distribution of the battery should be considered in the structural design.

3.4. Cross-media propulsion technology

The cross-media propulsion system must have the ability to work continuously and stably in two different media (air and water), and provide enough power to support medium and speed switching. However, the current aviation, aerospace and navigation propulsion systems cannot meet the above requirements, because the working principles and methods of the propulsion system in different media are different. So, one simple combination is to add two sets of propellers to the vehicle, one for the air and one for the underwater, which obviously increases the load, and is not very efficient. We know that aquatic propellers cannot provide power in the air, but aerial propellers can provide some propulsion underwater, so people designed some aquatic-aerial unmanned vehicles that use only a set of air propellers to provide propulsion in both air and water. And to make it easier for the vehicle to exit the water, water jet could be added into the vehicle.

3.5. Material technology

In order to make vehicles to have better performance intelligent materials could be use when build them. The main smart materials are shape memory materials, magnetostrictive materials, piezoelectric materials, electric (magnetic) rheological fluid materials. They can sense environmental changes and change one or more of their performance parameters at the same time, making the expected deformation that adapt to the changing environment.

Vehicles may suffer great impulse force when they enter the water. In order to dissipate the impact energy and prolong the service life of the vehicle, the configuration form and material technology of energy absorption elements should be studied and used.

4. Conclusion

Aquatic-aerial unmanned vehicles can be used in water environment monitoring and disaster response, and also have many important applications in oceanography, reservoir management, agriculture and other fields. The current water quality monitoring methods are time-consuming and laborious. However, by using aquatic-aerial unmanned vehicles, we can get a much faster response than using only UAVs or UUVs. Because it can do the air and water monitoring work independently, and can autonomously cross multiple independent water areas. Therefore, after collecting samples, recording data or videos in one water area, the water can be quickly transferred from the air to the next target water area to continue collecting information, so that the water quality information of different locations can be provided to the base station in a relatively short time. This efficient working mode is especially critical in disaster response such as water pollution.

Aquatic-aerial unmanned vehicles can also be used as communication relays for shore bases, surface ships and underwater submarines. Because it is difficult for submarine to communicate with the outside world, and it is easy to be exposed if it surfaces. With its good stealth and strong mobility, the water-air robot can also be used to collect maritime intelligence.

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