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Research and Applications of Autonomous Underwater Vehicles

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Abstract:

Autonomous Underwater Vehicle (AUV) technology has been developed in the field of underwater surveying over the past decades. Today as climate change and the energy crisis becoming increasingly urgent matters. Simultaneously, as technology is moving towards data-driven digitization, AUV technology is expanding into several other fields. This paper provides an overview of the current development of AUVs. It discusses the strength of AUV technology, such as high survey accuracy, large operational range and low operational costs compared to other surveying methods. It also addresses limitations, including battery technology constrains and wireless communication challenges. This paper will also introduce future areas of development based on the limitations, such as fuel cell, underwater scanning and mapping, underwater autonomous navigation, and bio-mimicry technology. Finally, based on the currently technology developments of AUVs, discuss the currently fields of application such as oceanography, underwater mapping and imaging and future fields of applications such as fisheries and use in underwater industrial inspections.

Keywords: Autonomous Underwater Vehicle; Underwater Navigation; Fuel Cell.

1. Introduction

70% of earth's surface is covered by ocean, and currently humans have explored only 20% of the oceans. Recently, with climate change and the energy crisis becoming increasingly pressing matters, and as technology are moving in the direction of data-driven digitization, people have developed and increasing interest in the fields of marine biology, oceanography surveys and ocean engineering. Before the adoption of AUVs, oceanography surveys and underwater explorations were primarily done using maned submersibles, remotely operated vehicles (ROV) or by shipboard or ship towed sonar equipment, these traditional methods had the limitations of limited operation time, high operational cost, reliance on mother ship and limited mobility. Autonomous Underwater Vehicles (AUVs), on the other hand, can dive uncontrolled to depths deeper than manned submersibles, and carry out continuous operations for several hours to several days in the extremely harsh environment of the deep sea. In addition, AUVs can also use terrain tracking and systems to dive to a depth of less than 5 meters from the seabed, and combined with on-board sensors, they can complete high-precision mapping and exploration operations with up to twice the accuracy of traditional ship-borne instruments.

Consequently, AUV technology has been increasingly adopted in various fields, including marine enviormental explorations, marine resources exploration and military applications. However, there is still room for development of underwater AUV technology, due to the current limited fuel cell technology, it is impossible to realize the AUV completely separated from the mothership for a long time, and at the same time, due to the current limited underwater wireless communication technology, the underwater AUV can only navigate and detect through its own program, and cannot realize real-time data transmission. Finally, materials and production technologies have also led to the high cost of AUVs, making them impossible to mass-produce [1]. In summary, while AUV technology has been increasingly adopted in various fields, including marine environmental exploration, marine resource exploration and military applications.

2. The basic structure of Autonomous Underwater Vehicle (AUV) technology

AUVs can be defined as underwater machines that can be unmanned and unfettered by cables, and can use onboard programs and algorithms to propel themselves and complete missions. Therefore, the basic hardware of an underwater robot consists of four parts: energy storage, external structure, propulsion system, motion system, and sensing system, and the basic software system consist of a control system and a navigation system [2].

The energy storage system of the AUV is responsible for powering all its systems. Currently, most AUVs use lithium-ion batteries.However there is a trend towards developing fuel cell technology for future energy storage solutions. The role of the outer body structure of the AUV is to protect all the electronic parts of the underwater robot as a sealed and compression-resistant shell [1]. The structural framework of most current AUVs is torpedo-like, like the first AUV - the SPURV of 1973, or the Autosub6000 of the United Kingdom. In the past 10 years, there have been more spherical, oval AUVs such as MIT's "Omni-Egg", the main advantage of this type of drone compared to the torpedo shape is that it is highly maneuverable and can operate in tight or hard-to-reach places. The current form factor development is mainly focused on improving efficiency and reducing drag, thereby extending battery life and operating time. In addition, AUVs that detect marine ecology will use biomimetic technologies to reduce the alarm of marine life, such as the robotic fish "Sofi" in 2018. While most current AUVs use propellers and rudder propulsion systems, bionic drones such as the robotic fish "Sofi" use multiple hydraulic drives to simulate the swing of a fish's tail [1]. The motion system is mainly responsible for the steering of the entire machine. Sensing systems are responsible for detecting and transmitting data, but underwater wireless communication technology is currently limited, so AUVs can transmit data while on the surface.

3. Characteristics of AUVs

AUVs can operate independently without reliance on a mothership. They can dive to suitable depths using airborne sensors, navigation systems, and terrain tracking programs. This capability allows for higher accuracy, lower cost, wider operation range, and longer operation time compared to traditional shipborne mapping systems. However, challenges remain, including limitations in fuel cell technology, wireless communication, and high production costs.

As shown in Fig. 1, the mapping time of the mothership-based operation longer. This is because the traditional towed systems require the mothership to make multiple turns during the mapping process. Moreover the turning speed of the mothership is much slower than that of the AUV. At the same time, the overall maintenance and operation costs of most manned carriers are higher, resulting in higher dispatch costs than smaller AUVs. In addition, towing probes are often required to be tracked by a second ship due to their location at a distance behind the mothership while the carrier is moving, further increasing costs. For these reasons, the cost of detection operations by underwater robots is 45% that of traditional towed detection [2].

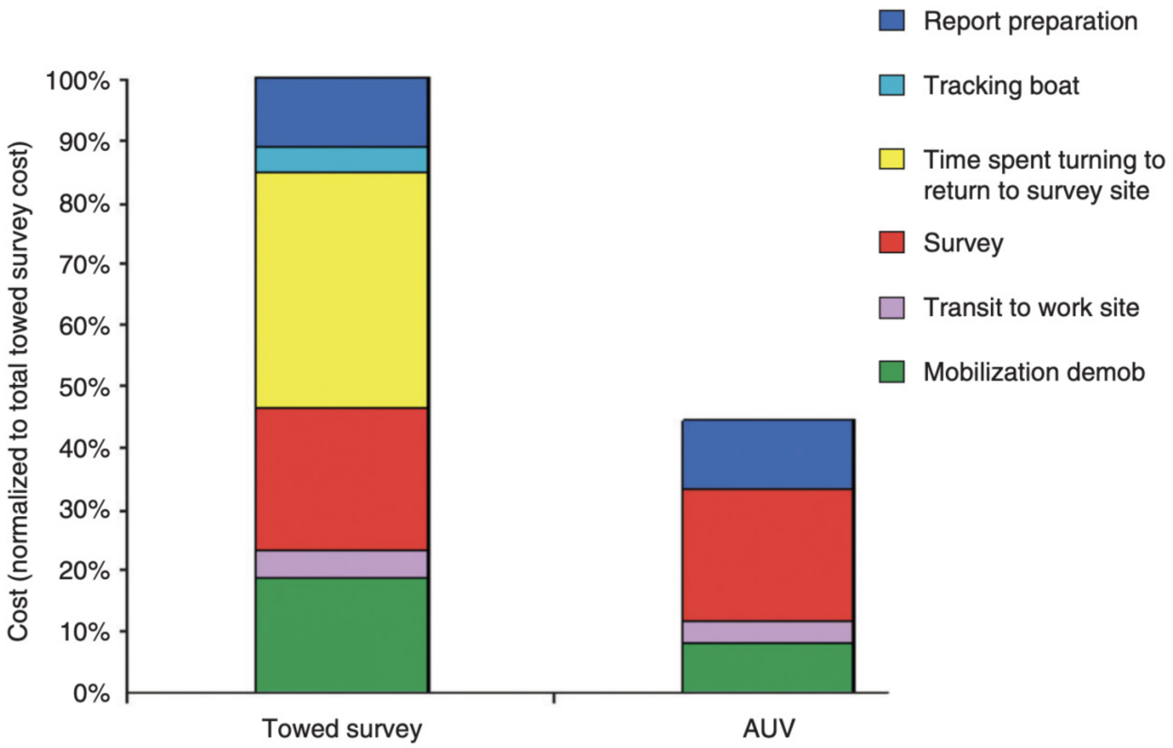

Fig. 1 Cost comparison of traditional towed survey with AUV survey [2].

Some deep-water AUVs, like the UK's Autosub6000, can dive to depths of 6000 meters. Unlike traditional towed or ship-borne detectors, these AUVs can maintain a suitable distance from the seabed while operating. This means that AUVs can achieve twice the accuracy of traditional towed or ship-borne detectors for underwater mapping operations. As a result, ROVs can utilize a wider variety of instruments such as multibeam echosounders, sub-bottom profilers, and other mission-specific instruments and tools compared to instruments such as side-scan sonars and cameras used in traditional detection techniques. Allowing for more accurate and detailed mapping of the marine environment.

Finally, because the AUV does not need to be operated by personnel after launch, the operation time of the AUV is greatly extended, and the AUV can continue to operate on its own for several days until the power is exhausted, which not only reduces the operating cost, but also has a greater degree of freedom of movement and operation range compared with remotely operated vehicles (ROV) that is bound by the cable.

4. Current progress and Future direction of AUV technology

4.1 Fuel Cell Technology

Currently, most underwater robots on the market used lithium batteries as the energy source of the whole vehicle, but due to the limited capacity of lithium batteries, the operation time of AUVs is limited. At the same time, underwater AUVs with short battery life needs to be tracked by a mothership, increasing operating costs. However, fuel cell technology has much larger potential. Due to their higher energy density than most batteries, as shown in Fig 2, fuel cells allow AUVs to have a longer range. Currently, advanced AUVs on the market, such as the HUGIN 3000 AUV, use lithium-polymer (lithium-polymer) batteries to achieve operational times of 70 hours and 220 nautical miles with all sensors working. Fuel cell technology can allow drones to last up to 2-3 weeks , for example, in 2018 the U.S company General Atomics used the Aluminum Power System (ALPS) completed a 46-day test in which the system uses oxygen as fuel to produce helium using the reaction of oxygen with water and aluminum [3,4].

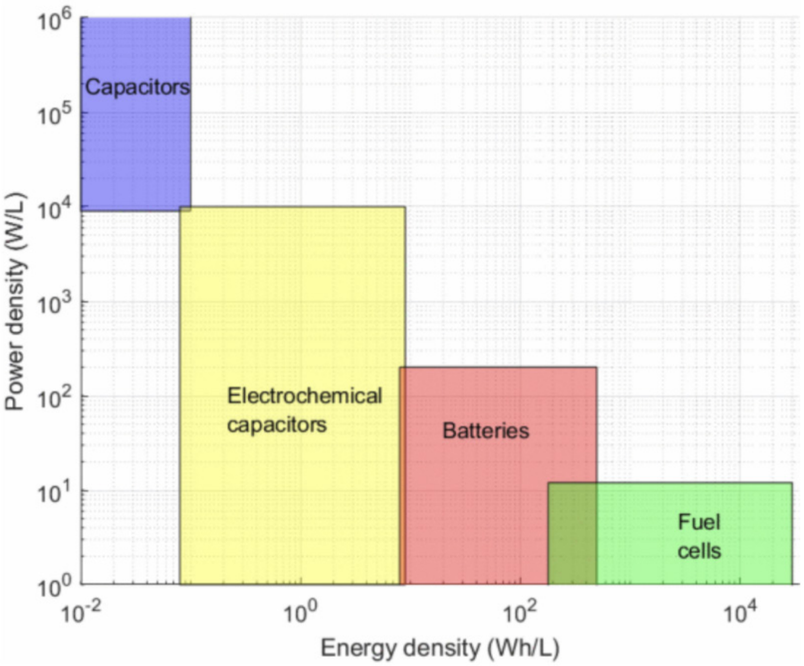

Fig. 2 Comparison of energy and power densities of the four energy storage technologies [5].

Currently, fuel cell research for AUVs primarily focuses on Proton Exchange Membrane (PEM) technology. PEM fuel cells are relatively mature compared to other fuel cell types and have been widely adopted in electric vehicles. They offer high energy density, which is maintained even in the low-temperature environment of the deep sea [6].

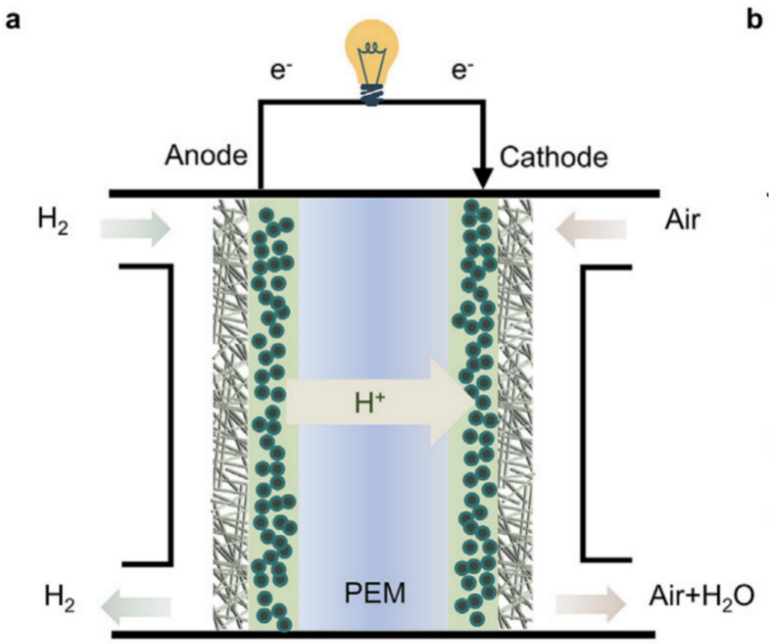

Fig. 3 Diagram of the basic operating principle of a proton exchange membrane fuel cell [7].

The fuel for proton exchange membrane fuel cells is hydrogen and oxygen. Due to hydrogen's low density, improper storage can lead to excessive AUV buoyancy. Moreover, as fuel is consumed during the mission, the AUV's density and center of gravity change, presenting additional challenges. Therefore, the biggest problem with the current use of this technology in AUVs is the storage method of hydrogen and oxygen, as shown in Fig. 3 [7]. There are many solutions on the market, combining a variety of qualitative factors such as energy density, buoyancy, buoyancy variation, system simplicity, etc., and it is best to store a pressure tank lined with synthetic materials at a high pressure of 700 bar. Oxygen storage is similarly difficult, and a pressure tank lined with synthetic materials at a high pressure of 300 bar is best taken into account, but it is noted that hydrogen peroxide has an advantage in terms of depth freedom because it is a liquid and cannot be stored in a hard container [8].

4.2 Underwater mapping techniques

Over the past three decades, AUVs have primarily been employed in ocean and seabed exploration, leading to significant maturation of their mapping technologies. Underwater AUVs are equipped with different detection instruments and algorithms according to different application scenarios, and the current technology is mainly suitable for the detection and mapping of benthic habitats, marine geology, fisheries, water columns, and continental ice in Polar Regions [9]. In the mapping of benthic habitats, traditional sensor technology often utilizes side-scan sonar technology. However, while the accuracy of this technology is limited in ship borne detection systems, AUVs can be closer to the habitat, more data can be collected in combination with other imaging technologies, such as multi-beam swath bathymetry, backscatter, conductivity, temperature, depth, chlorophyll, and colored dissolved organic matter (CDOM) [9]. This results in a more comprehensive and accurate mapping of the detected benthic habitats. In 2011, Raineault et al. used bathymetric sonar and side-scan sonar to map shallow bottom habitats along the Delaware Bay and Atlantic coasts of United States, using bathymetric sonar data to derive information about sediment size, texture, and multiple ecosystems in the area, such as oyster beds and coral reefs [10].

For marine geological detection, AUVs can integrate various technologies with sonar. These include laser scanning, chemical detectors, gravity gradiometers, and sub-bottom profilers. This combination enables comprehensive 3D modeling of the seabed and its underlying conditions. The application of AUVs in the field of fishery originated at the beginning of the 21st century, and the current application of AUVs in the field of fishery is mainly to investigate the number of fish in a certain ecology. The traditional technique in this field is to use shipboard acoustic sensors to detect the density of fish populations and thus infer the number of fish in a certain area, which can lead to detection of dead spots or artificial dive recordings [11]. However, the installation of this technology on an AUV allows the sensory to measure from multiple angles at a closer distance, which can provide information on the size of different species of fish and the dynamics of fish schools [9]. AUVs can also measure individual fish using stereo photogrammetry. In addition, the washing drone can also use the on-board receiver to generate the movement trajectory of the fish that has been installed with a transponder, which is convenient for researchers to study the fish. The horizontal stability of AUVs minimizes vertical position errors when measuring water column flow, enhancing the accuracy of such measurements. Currently, most AUVs employ Conductivity-Temperature-Depth (CTD) profilers to detect water column characteristics and other basic information in the aquatic environment. To detect the velocity of the water flow in the water column, Acoustic Doppler Current Profilers (Acoustic Doppler Current Profilers; ADCPs), small AUVs are usually detected with the Doppler effect generated by 1200kHz sound waves in water currents, with a detection range of up to 25-40 meters, while large AUVs usually use 150-300kHz sound waves to reach a detection range of 200 meters [9]. The future development of this field is mainly in the measurement of turbulence in the water column. In recent years, people's exploration and understanding of the base has also increased. AUV technology is crucial in understanding the polar continental ice, and it is difficult for traditional shipborne sonar technology to detect the polar ice, which usually requires icebreakers, helicopters and military submarines to cooperate, so the detection cost also increases significantly. At present, ice shelf imaging and mapping technology mainly relies on multibeam echo sounders [10]. Due to the low failure tolerance of these operations, most of the research directions in this field are in the reliability and endurance of AUVs, such as the 1000 km survey mission carried out by Canada in the Arctic region of Canada in 2010 [9].

4.3 Underwater Positioning and Navigation Technology

Underwater positioning technology is fundamental for AUVs, enabling them to navigate pre-planned routes and maintain accurate positioning The most basic navigation system for AUVs is the Global Positioning System (GUSS; GPS), Inertial Navigation System (Inertial Navigation System; INS), GPS cannot work effectively underwater because it relies on satellite signals, so GPS navigation is only suitable for precise positioning when AUVs surface. The INS navigation system is based on gyroscope technology, so it does not require any reference object, so it can work as usual underwater, but compared with the accuracy of GPS 1-10 meters, the INS system is lower, so the two are usually combined into an AUV to achieve the basic position positioning and navigation of the drone. To further improve the accuracy of navigation and positioning, Doppler Velocity Log (Doppler Velocity Log; DVL) in combination with the above means [12]. The DVL works by emitting sound waves and calculating the drone's velocity using the Doppler Effect that reflects back to the machine from the seafloor. However, the scheme will have a large error in deep water, and the measured velocity is relative to the water, not to the seabed. In order to improve the accuracy of the above technology, sound beacons and algorithms are used to improve the accuracy. Costanzi et al.'s 2014 experiment, which combined algorithms and ship borne acoustic beacons, showed a significant improvement in accuracy compared to no assistance, as shown in Fig. 4 [13].

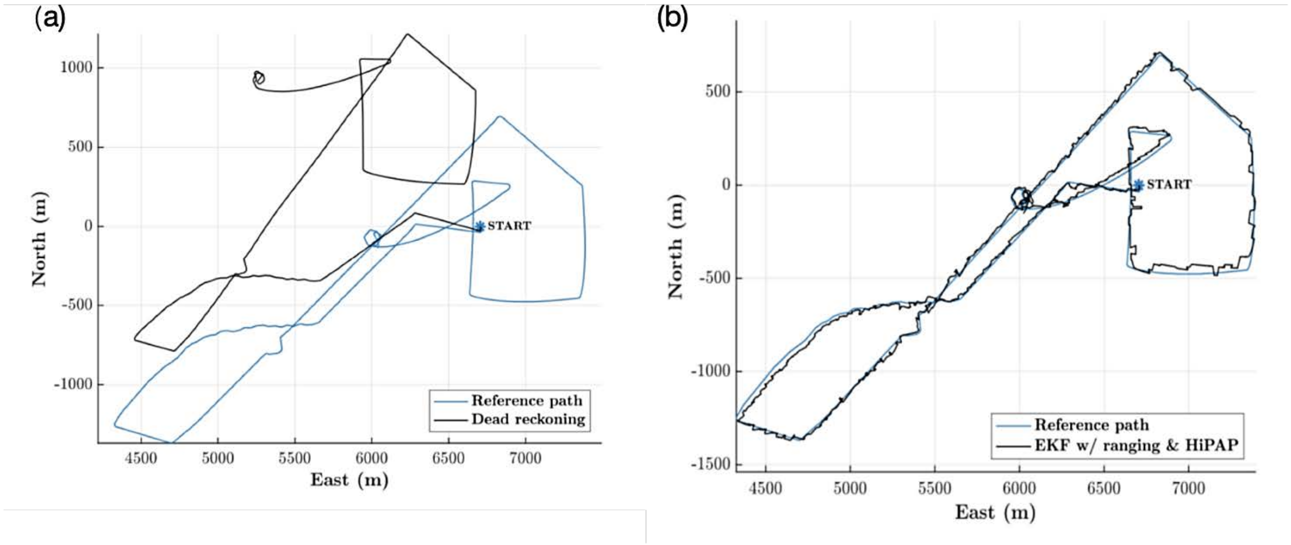

Fig. 4 Underwater Navigation Techniques (a) Dead reckoning. (b) Algorithm and Acoustic Beacons aid [13].

The final navigation system type is Terrain Based Navigation (TBN). It combines depth sensors, laser or radar altimeters, and onboard topographic data to measure seafloor morphology and achieve positioning [14].

4.4 Bio-mimic technology

AUV bionic technology is primarily used for close observation of underwater ecology. By mimicking the locomotion of marine organisms, bio-mimic technology eliminates the need for propellers. This approach avoids cavitation thus minimizing noise, and allows for close observation of marine habitats without disturbing the resident organisms [15].

Bionic fish is a relatively mature technology in the field of underwater robot bionics, and this kind of bionic AUV imitates the driving mode and appearance of various fish. In the early days of this technology, most of the servants or DC motors were used to drive the rigid body fishtail of the robot, such as the “icthus” robot fish developed by Yang et al. in 2011, but the degree of biomimetic technology is low. In recent years, mollusc bionic fish technology has advanced significantly. In 2014, Ming et al. successfully imitated sea snake movements using soft drives and composite materials. Katzschmann et al. developed ‘Sofi’, a soft-tailed robotic fish, in 2018. More recently, Anand et al. created a cuttlefish-inspired robot in 2024. Due to the limitations of the robot’s shape and size, such bionic AUVs cannot carry a large number of sensors and instruments [16].

The main advantage of the bionic turtle AUV is its high and precise maneuverability at low speeds, and it can also levitate in the water [17]. For example, the U-CAT bionic turtle robot developed by Chemori et al. in 2016 can achieve six degrees of freedom through four individually driven flippers [18]. At the same time, compared with propellers or propellers, the drive of such bionic flippers not only has the advantage of low noise, but also greatly reduces the sediment raised during close motion from the seabed, which is more conducive to the application of visual sensory on the seabed or in small spaces [18]. In recent years, more biomimetic deformed limbs for turtle AUVs have also been studied, such as the deformed flipper developed by Baine et al. in 2019, which may enable AUVs to be used amphibious [19].

5. Future application scenarios of AUVs

At present, with the continuous development of sensory technology, AUVs can also play a role in underwater industrial inspection. In this regard, there have been experimental results in the examination of sub-sea pipelines. In 2018-2020, Rumson carried out a pipeline inspection project based on AUVs on seven pipelines around Norway. The project completed the inspection of 180 kilometers of pipelines, achieving the world’s first completely unmanned “cross-horizon” pipeline inspection [20]. Due to the high requirements for AUV navigation accuracy for pipeline inspection, this project uses INS, GPS, DVL, and other navigation systems that rely on punctuation features. In order to accurately inspect the pipeline, the project combined a variety of instruments in Section 3.2 of this paper, including but not limited to multi-beam echo sounder, side-scan sonar, synthetic aperture sonar, laser scanner, camera, and other sensors, to successfully achieve a 3D reconstruction of the pipeline’s height and detect problems such as pipe suspension and anode depletion [20].

6. Conclusion

In summary, underwater AUVs achieve higher detection accuracy compared to traditional methods by employing innovative technologies. These include multi-beam echo-sounders, sub-bottom profilers, sonars, Doppler current profilers, conductivity-temperature-depth analyzers, and acoustic sensors. These advanced instruments enable more precise and comprehensive underwater exploration. The mapping and imaging methods mentioned above mean that underwater AUVs can be used in the fields of seabed exploration, benthic habitat exploration, ocean water column detection, and polar ice detection, and can be used in the field of underwater industrial exploration in the future. Navigation technologies such as GPS/INS for AUVs are in a mature stage, and the future development direction lies in the use of algorithms to improve navigation accuracy. At present, AUVs on the market use lithium battery technology, and the endurance performance of this technology is limited, so the future development direction lies in fuel cells. Finally, in order to enable AUVs to be used in marine ecological exploration in the future, biomimetic technology is a major development direction in the future, with an increased level of automation by incorporating a higher level of algorithm when it comes to decision making, resulting in a decreased operational cost when it comes to completing missions.

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