Research on the Development and Application of Underwater Unmanned Aerial Vehicle Technology

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**Abstract.** Marine exploration is of great significance. Traditional manned submersibles have drawbacks such as high costs and limited diving depths, leading to the emergence of underwater drones. However, most research on underwater drones focuses on individual technologies, lacking systematic reviews. This paper conducts research on the technological development and application of underwater drones. By using the literature research method, relevant literature is retrieved from authoritative databases. Through interdisciplinary integration and analysis, combined with real marine data, the key technologies (mechanical design, integration of inertial navigation and sonar, communication technology) of underwater drones are analyzed. The application fields (seabed topography mapping, oil and gas pipeline inspection) and cases are also examined. The technical challenges (communication difficulties, insufficient autonomous decision-making) and countermeasures are discussed. The research finds that underwater drones have made progress in key technologies and have improved efficiency and reduced costs in applications. In the future, in the short term, battery technology and communication protocols can be optimized. In the long term, it is expected that AI and Unmanned Underwater Vehicles (UUVs) will be integrated to build an underwater Internet of Things ecosystem.

# Introduction

Human exploration of the ocean is still in its infancy. The marine environment is complex and changeable, featuring extreme conditions such as high pressure, low temperature, darkness, and strong corrosiveness. Traditional manned submersibles, although having played a significant role in marine exploration, are limited by high costs, depth limitations, and considerable risks to personnel safety, making it difficult to meet the growing demands of marine development. Against this backdrop, underwater drones have emerged as a new force in marine exploration. Underwater drones, also known as unmanned underwater vehicles (UUVs), are unmanned devices capable of autonomously or remotely performing tasks underwater. With their advantages of autonomy, low cost, and strong adaptability, they effectively make up for the shortcomings of traditional manned submersibles and have become key technological carriers in deep-sea exploration, underwater engineering maintenance, and marine resource development. Despite significant progress in underwater drone technology in recent years, current research mostly focuses on individual technologies such as navigation, energy systems, and communication technologies, lacking systematic reviews and studies [1, 2]. With the continuous expansion of underwater drone application scenarios, how to better meet the needs of different application scenarios and solve the problems faced in practical applications has also become an urgent research topic. Therefore, by integrating multidisciplinary literature and deeply analyzing the correlation between technological innovation and the application scenario expansion of underwater drones, it is of great theoretical and practical significance to promote the further development and wide application of underwater drone technology.

Abroad, countries and regions such as the United States, Russia, and Europe have started early in underwater drone technology research, investing substantial resources and achieving numerous pioneering and leading results. The United States leads the world in underwater drone technology, with a comprehensive and advanced research and development system and extensive application practices. The U.S. Navy vigorously develops underwater drone technology, viewing it as an important force in future naval warfare. European countries such as Norway, France, and the United Kingdom also have their own characteristics in underwater drone technology research. Norway's REMUS and HUGIN series underwater drones are renowned for their high-precision navigation systems and excellent adaptability to marine environments, widely used in marine research and underwater mapping. France's Alister series underwater drones have unique advantages in acoustic detection and communication technologies, capable of efficient data transmission and precise target detection in complex marine acoustic environments. The United Kingdom's Autosub series underwater drones excel in long-duration and deep-sea operation capabilities, providing important technical means for deep-sea scientific research. Although China started relatively late in underwater drone technology research, it has developed rapidly in recent years and achieved remarkable progress. With the country's high emphasis on marine strategy and increasing investment in marine science and technology research, numerous research institutions, universities, and enterprises in China have actively participated in the research and development of underwater drone technology, forming a close integration of industry, academia, and research. Northwestern Polytechnical University has made significant breakthroughs in bionic underwater drone technology, developing the "Manta Ray-like Soft-bodied Underwater Vehicle", which mimics the body structure and movement of manta rays, featuring high bionic characteristics, capable of flexible movement underwater, efficient energy utilization, and low noise operation, with broad application prospects in deep-sea exploration and marine environment monitoring. The "underwater helicopter", developed by research teams from Zhejiang University and the Shenyang Institute of Automation of the Chinese Academy of Sciences, among others, is a new concept unmanned autonomous underwater vehicle with complete independent intellectual property rights in China. It can work on the seabed for a long time and has unique functions such as free take-off and landing, hovering at a fixed point, full-range turning, and bottom-hugging navigation. It has broken through the technical limitations of traditional underwater drones and provided a new solution for underwater operations [3].

This paper adopts the literature research method, with "underwater drones", "UUV technology", and "marine robots" as the core keywords. It conducts literature retrieval in authoritative academic databases such as CNKI and Web of Science, with the time range limited to 2003 - 2025. At the same time, the retrieved literature is restricted to core journals and conference papers indexed by "CSSCI" and "SCI".

# Analysis of Key Technologies for Underwater Unmanned Aerial Vehicles

The most crucial technology is mechanical design. In the mechanical design of underwater unmanned aerial vehicles, lightweighting and modularization are two important development directions, which play a key role in enhancing the performance of underwater unmanned aerial vehicles.

With the continuous advancement of materials science, lightweight materials such as carbon fiber have been widely used in the manufacturing of underwater unmanned aerial vehicles. Carbon fiber is a new type of fiber material with a carbon content of over 95%, featuring low density, high strength, high stiffness, corrosion resistance, and fatigue resistance. Compared to traditional metal materials, the density of carbon fiber is only about 1/3 of that of aluminum alloy, but its strength is much higher, enabling it to significantly reduce the weight of underwater unmanned aerial vehicles while maintaining structural strength [4]. This not only helps improve the maneuverability of underwater unmanned aerial vehicles, allowing them to navigate more flexibly in water, but also reduces energy consumption and extends the flight duration, thereby enhancing the operational efficiency and application scope of underwater unmanned aerial vehicles.

The second key technology is the integration of inertial navigation system (INS) and sonar in the navigation and positioning of underwater unmanned aerial vehicles, which plays a crucial role in significantly improving the positioning accuracy and enabling them to accurately perform tasks in complex underwater environments. The inertial navigation system is an autonomous navigation system based on Newtonian mechanics principles, which determines the position, velocity, and attitude information of the carrier through measuring its acceleration and angular velocity through integration. The core components of the INS include gyroscopes and accelerometers, which measure the angular velocity of the carrier and its acceleration, respectively. Due to its independence, good concealment, and strong anti-interference capabilities, the INS can continuously provide navigation information in underwater environments.

However, the INS also has some limitations. Over time, its positioning errors will gradually accumulate because the integration process continuously amplifies measurement errors, resulting in a decrease in positioning accuracy. During long underwater voyages, the error of the INS may reach several kilometers or even larger, seriously affecting the positioning accuracy of underwater unmanned aerial vehicles. Sonar is a device that uses the propagation characteristics of sound waves in water to detect and locate targets, and it obtains information such as distance and direction of the target through emitting sound waves and receiving reflected sound waves. Sonar has the advantages of long transmission distance in water and low signal attenuation, and can effectively detect underwater targets and terrain, providing important positioning references for underwater unmanned aerial vehicles. Sonar also has certain limitations. Its measurement accuracy is susceptible to changes in ocean environment factors, such as water temperature, salinity, and water flow, which can cause changes in the propagation speed of sound waves and affect the measurement accuracy of sonar. The measurement range of sonar is limited, and its ability to detect distant targets is relatively weak [5].

The third key technology is communication technology. To overcome the challenges of underwater communication and improve the rate and stability of underwater communication, researchers have continuously explored and developed new communication technologies, achieving a series of significant breakthroughs and progress. These new technologies have shown excellent effects in practical applications and provide new solutions for the communication of underwater unmanned aerial vehicles. Fiber optic communication technology has been increasingly applied in the communication of underwater unmanned aerial vehicles, bringing new hope for solving underwater communication problems. Fiber optic communication uses light to transmit information in optical fibers, featuring high transmission rate, large bandwidth, and strong anti-interference capabilities. In underwater environments, fiber optic communication can achieve high-speed and stable data transmission, effectively overcoming the problems of rapid signal attenuation in wireless communication and low communication rate in acoustic communication. The transmission rate of fiber optic communication can reach Gbps or higher, a significant leap compared to the low rate of acoustic communication. Through optical fibers, underwater drones can quickly transmit a large amount of collected data, such as high-definition images, real-time videos, and complex marine monitoring data, to the surface control station or other receiving devices, significantly improving the efficiency and timeliness of data transmission. Optical fiber communication has strong anti-interference capabilities and can operate stably in complex underwater environments, reducing signal distortion and error rates, and enhancing communication reliability.

# Application Areas and Case Analysis of Underwater Unmanned Aerial Vehicles

The most widely and commonly used application is underwater topographic mapping. Underwater topographic mapping is an important basic work in marine research, and it is of crucial significance for understanding the marine geological structure, marine ecological environment, and the distribution of marine resources. Underwater unmanned aerial vehicles play an indispensable role in underwater topographic mapping. Taking the "Jiaolong" as an example of cooperative UUV, their application and achievements in this field can be more clearly demonstrated. The "Jiaolong", as a manned underwater vehicle independently designed and integrated by China, has achieved remarkable achievements in deep-sea exploration. The UUV cooperating with "Jiaolong" further expanded its detection capabilities and improved the efficiency and accuracy of underwater topographic mapping. These cooperative UUVs possess advanced measurement technologies and equipment, such as high-precision multi-beam bathymetry systems and side-scan sonars, which can conduct comprehensive and detailed measurements and imaging of the underwater topography. In practical applications, the "Jiaolong" cooperative UUV and "Jiaolong" cooperate with each other, leveraging their respective advantages. "Jiaolong", relying on its manned advantage, can carry researchers directly to specific areas on the seabed for on-site observation and sampling. The cooperative UUV, with its flexibility and efficiency, conducts rapid mapping of the underwater topography over a large area. When mapping the topography of a certain deep-sea area, the cooperative UUV first uses the multi-beam bathymetry system to conduct large-scale measurements of the area, obtaining the general outline and depth information of the seabed topography.

Through the scanning of the seabed surface's topographic features by the side-scan sonar, high-resolution seabed images are generated, providing data support for subsequent detailed analysis. The "Jiaolong" cooperative UUV has achieved fruitful results in underwater topographic mapping. Through the analysis and processing of a large amount of underwater topographic data, high-precision seabed topographic maps have been drawn, providing important basic materials for marine geological research. In the mapping of a certain sea area in the South China Sea, new submarine mountains and trenches were discovered, which are of great value for in-depth study of the geological evolution and plate movement of the South China Sea [6]. The cooperative UUV can also conduct detailed exploration of the submarine geological structure, providing key information for marine resource exploration. Through the analysis of the composition and structure of the seabed rocks, it is helpful to find potential mineral resources and oil and gas resources. The second relatively widespread application is oil and gas pipeline inspection. Underwater unmanned aerial vehicles play an important role in the field of oil and gas pipeline inspection. Through actual cases, the significant advantages of these vehicles over traditional inspection methods can be clearly seen. In a large-scale offshore oil and gas field development project, underwater unmanned aerial vehicles were used for the regular inspection of oil and gas pipelines. The oil and gas pipelines in this project were laid in a complex seabed environment, with a length of several tens of kilometers. Traditional inspection methods faced many challenges. Traditional oil and gas pipeline inspection methods mainly relied on divers or large inspection equipment. Divers had obvious limitations due to the complex seabed environment, their activity range and working time were greatly restricted, and diving operations had high safety risks. Divers might face dangers such as water pressure, low temperatures, and eddies. For long-distance oil and gas pipelines, the efficiency of divers' inspection was extremely low, unable to meet the needs of large-scale pipeline inspection. Large inspection equipment had certain advantages in detection capabilities, but the deployment and operation costs were high, requiring professional vessels and a large number of personnel, and the equipment's flexibility was poor, unable to adapt to complex seabed topography and narrow pipeline spaces.

In this project, underwater unmanned aerial vehicles were equipped with advanced inspection tools such as high-definition cameras, sonar sensors, and corrosion detection equipment. During the inspection process, the underwater drone can quickly and flexibly cruise along the oil and gas pipeline, using high-definition cameras to take comprehensive photos of the pipeline surface, and transmitting the images in real time to the ground control center. The staff can clearly observe the surface condition of the pipeline through the images and promptly detect whether there are cracks, damages, or corrosion problems in the pipeline. The sonar sensor can detect the internal structure of the pipeline and accurately determine whether there are deformation or blockage hazards. The underwater drone can also use the corrosion detection equipment to precisely measure the corrosion degree of the pipeline, providing scientific basis for subsequent maintenance and repair work. Through the application of underwater drones, the efficiency of oil and gas pipeline inspection in this project has been significantly improved. Compared with traditional inspection methods, the underwater drone can complete the inspection tasks of long-distance pipelines in a short time, with the inspection speed increased by several times. The detection accuracy of the underwater drone is also higher, capable of detecting tiny defects and potential problems that are difficult to be detected by traditional inspection methods. The use of underwater drones has also significantly reduced the inspection cost, reduced the reliance on large-scale inspection equipment and a large number of personnel, and lowered the safety risks for divers. According to statistics, after applying underwater drones for oil and gas pipeline inspection in this project, the inspection efficiency has increased by more than 40%, the cost has been reduced by approximately 30%, achieving significant economic and safety benefits [7].

# Challenges and Solutions for Underwater Unmanned Aerial Vehicle Technology

The biggest challenge faced by underwater unmanned aerial vehicles compared to other types of unmanned aerial vehicles is communication technology. Among them, signal attenuation and low communication rate are the most prominent problems, which severely restrict the operation of the unmanned aerial vehicles. In the underwater environment, the propagation of radio signals is greatly hindered, and the attenuation speed is extremely fast. This is because seawater is a conductive medium with a high electrical conductivity. When radio signals propagate in seawater, they interact with the ions in the seawater, causing rapid energy loss of the signal. According to relevant theories and experimental research, the attenuation of radio signals in seawater is closely related to the frequency. The higher the frequency, the more severe the attenuation. High-frequency radio signals have extremely limited propagation distance in seawater, usually only a few meters or even less, which makes traditional communication methods based on high-frequency radio impossible to achieve underwater [8].

To more intuitively understand the attenuation of underwater radio signals, taking common ultrashort wave communication as an example, in the air, ultrashort waves can propagate for thousands of meters or even farther, and the signal strength can remain at a certain level, thus enabling stable communication. However, in the underwater environment, ultrashort wave signals lose signal strength sharply after propagating only a few meters, and are almost impossible to be effectively received. This huge difference fully demonstrates the fast attenuation characteristic of underwater radio signals and the significant challenges it brings to underwater unmanned aerial vehicle communication. Sonar communication is currently one of the main methods of underwater unmanned aerial vehicle communication, but its communication rate is low, generally with a transmission rate of ≤ 10 kbps, which significantly limits the information transmission capacity of underwater unmanned aerial vehicles. The propagation speed of sound waves in water is relatively slow, approximately 1500 m/s, which is far different from the propagation speed of electromagnetic waves in air (approximately 3 × 10^8 m/s).

Due to the propagation characteristics of sound waves, their ability to carry information is limited, resulting in difficulty improvement of the communication rate. During data transmission, complex processing procedures such as modulation and demodulation of sound wave signals are required, which further increases the time delay of signal transmission and reduces communication efficiency. The underwater environment is complex and variable, with various interference factors such as the activities of marine organisms, changes in water flow, and reflection of the seabed terrain. These factors can interfere with sound wave signals, causing signal distortion, increased bit error rate, and further reducing the reliability and rate of communication. The second challenge to be faced is autonomous decision-making ability. In complex marine environments, optimization of mid-path planning algorithms and insufficient generalization ability of AI models are prominent problems, which have a significant impact on the operational efficiency and safety of underwater unmanned aerial vehicles. When performing tasks, underwater unmanned aerial vehicles need to plan the optimal navigation path in real time based on changes in the surrounding environment to avoid colliding with obstacles, bypass dangerous areas, and complete tasks efficiently. However, current path planning algorithms have problems such as high computational complexity, poor real-time performance, and insufficient path optimization when facing complex marine environments. Due to the numerous factors to consider, such as ocean current fields, seabed terrain, and obstacle distribution, the computational load of these algorithms will increase sharply in complex marine environments, resulting in long calculation times that cannot meet the real-time requirements of underwater unmanned aerial vehicles. Uncertain factors in complex marine environments, such as sudden changes in ocean currents and the appearance of unknown obstacles, can significantly reduce the performance of traditional path planning algorithms, making it difficult to plan the optimal path.

To break through the bottleneck of underwater drone communication technology, developing low-power communication protocols is a crucial innovative idea. The low-power communication protocol aims to reduce energy consumption during the communication process while ensuring communication quality, in order to extend the endurance of underwater drones and meet their long-term operation requirements. Researchers optimize the modulation and demodulation method of communication signals, adopt efficient coding algorithms and energy-saving transmission strategies to reduce energy loss during the communication process. By using orthogonal frequency division multiplexing (OFDM) technology, high-speed data streams are divided into multiple low-speed sub-data streams and transmitted simultaneously on multiple subcarriers, improving spectral utilization and reducing the energy demand for signal transmission. Utilizing adaptive modulation technology, the modulation method and encoding rate are dynamically adjusted according to the channel conditions to ensure communication reliability while reducing energy consumption. Through these technical means, the low-power communication protocol can effectively improve the energy utilization efficiency of the underwater drone communication system, providing a guarantee for its long-term stable communication in complex underwater environments. In terms of path planning algorithm optimization, in response to the shortcomings of traditional algorithms in complex marine environments, researchers have proposed various improvement strategies [9]. One common optimization method is to improve the heuristic function, which plays a crucial role in guiding the search direction in the path planning algorithm. By designing a more reasonable heuristic function, it can more accurately reflect the distance and direction relationship between the current position of the underwater drone and the target position, as well as consider the influence of marine environment factors on the path, such as ocean current fields and seabed topography, thereby improving the search efficiency of the algorithm and finding the optimal path faster. Introducing search space pruning technology is also an effective means to optimize the path planning algorithm. This technology divides and screens the search space reasonably, removing those search areas that are obviously unlikely to be the optimal path, reducing the search range of the algorithm, lowering computational complexity, and improving the real-time performance of the algorithm. In complex marine environments, using environmental information obtained from sensors such as sonar and radar to identify obstacle areas and dangerous areas, excluding these areas from the search space, enables the algorithm to focus more on searching for the optimal path within the feasible area. Dynamic weight adjustment strategies can also be adopted, adjusting the weight parameters in the path planning algorithm according to the real-time conditions encountered by the underwater drone during navigation, to adapt to different marine environments and task requirements. When encountering strong ocean currents, increasing the weight of the influence of ocean currents on the path, enables the algorithm to plan a more reasonable path, avoiding being swept away by the ocean currents, and ensuring that the underwater drone can complete the task safely and efficiently [10].

# Conclusion

This study provides a comprehensive and in-depth review of the development and application of underwater unmanned aerial vehicles (UAVs). In terms of technological development, underwater UAVs have made significant progress in key areas such as mechanical design, navigation and positioning, and communication technology. In mechanical design, the application of lightweight materials like carbon fiber and the design of modular structures have significantly enhanced the pressure resistance and maneuverability of underwater UAVs, enabling them to better adapt to complex underwater environments. In navigation and positioning technology, the integration of inertial navigation systems (INS) and sonar has improved positioning accuracy to a certain extent, but there is still a 5%-10% error in deep-sea environments. In communication technology, the rapid attenuation of underwater radio signals makes traditional radio communication methods difficult to implement underwater; while acoustic communication is one of the main communication methods, its rate is low, generally ≤ 10 kbps, severely limiting the information transmission capacity of underwater UAVs and becoming the main bottleneck in the communication field. Underwater UAVs face many technical challenges during their development. In terms of autonomous decision-making, path planning algorithms need to be optimized in complex marine environments to improve real-time and accuracy; the insufficient generalization ability of AI models leads to a decline in decision-making ability when facing complex and variable marine environments, affecting the operational efficiency and safety of underwater UAVs. In terms of technological innovation paths, developing low-power communication protocols, optimizing path planning algorithms, and enhancing the generalization ability of AI models are needed to break through technical bottlenecks and improve the performance and reliability of underwater UAVs.

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