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Advances and Applications in Underwater Robotics Technology

Kangjie Zhang

School of Information Science and Engineering, Harbin Institute of Technology, Weihai, 264200, China
2022210798@stu.hit.edu.cn

Abstract. As an important tool for ocean exploration and development, underwater robotics is more efficient, safer, and more reliable than human labor. In recent years, the development of marine resources has played an important role in various fields. However, the development of underwater robots is limited by the complexity of the underwater environment, the lack of endurance, and the fact that efficient communication technology and autonomous cruise technology still need to be developed. This paper adopts the methods of literature review and case study analysis to overview the underwater robotics research background and significance, the classification of underwater robotics technology, the status and research progress, and the main application results of underwater robotics, and analyze the future technical challenges facing this technology, and finally, to look forward to the future development trend. Underwater robots can perform high-risk or other tasks that are difficult for humans to perform directly, greatly expanding human cognition and ability to use the oceans.

Keywords: Underwater Robot, Ocean Exploration, Autonomous Control

1 Introduction

As the global demand for marine resources continues to rise and people's awareness of marine environmental protection increases, underwater robotics technology is gradually receiving widespread attention. The ocean is rich in energy, but human knowledge of the ocean is still the tip of the iceberg. Traditional human diving operations lack efficiency and safety, etc. With the booming development of robotics, underwater robots are becoming an important technical means for marine scientific research, resource development, environmental monitoring, emergency rescue, and military applications because of their ability to carry out highly efficient, safe, and reliable operations compared to humans. Underwater robotics research since the mid-20th century has made a lot of achievements: for example, civil use in emergency search and rescue in floods; military use in reconnaissance, defense, underwater communications, etc.; marine resources can be used for undersea oil fields, electrical and other resources development, monitoring of the marine ecosystem; scientific research can be used to explore the unknown new organisms, and so on [1]. However, there are still many new challenges in underwater robotics, such as reliability and

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durability, underwater communication and accurate positioning, energy supply and endurance, autonomous control and intelligent decision-making, multi-robot cooperation, and so on. The future of underwater robotics has a long way to go.

This paper adopts the research method of combining literature review and case analysis to summarise the status of underwater robotics technology by combining relevant domestic and international literature. Secondly, it summarises the main applications of underwater robots with typical cases. Finally, it analyses the challenges faced by underwater robots and the direction of future development. The purpose of this paper is to provide a systematic reference for the academic research and practical application of underwater robotics, hoping that underwater robotics can expand its diversified applications and promote its industrial development through multi-dimensional innovation and interdisciplinary integration.

2 Status of Underwater Robotics Research

Underwater robotics research in the sustainable development of marine resources, scientific research, environmental monitoring and protection, civil emergency rescue, national defense security, and many other areas of great significance, extensive market demand, and broad technical prospects. Underwater robots can be manned or unmanned, with or without cables. There are two main classification methods, as shown in Figs. 1 and 2. This paper mainly introduces three mainstream underwater robots in the current market: remotely operated unmanned vehicles (ROV), cable-free underwater robots (AUV), and autonomous/remotely operated underwater robots (ARV). A comparison of the key performance and characteristics of these three types of underwater robots is summarised in Table 1.

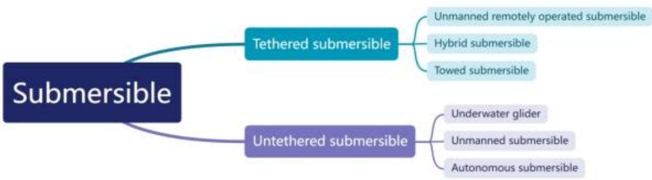

Fig. 1. Submersible division based on cable and cableless [2]

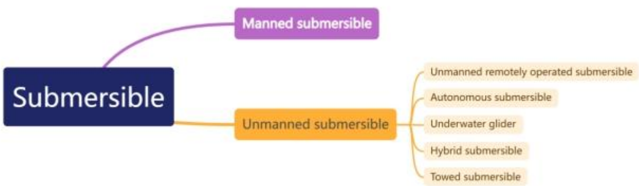

Fig. 2. Classification of submersibles division based on manned and unmanned [2]

Table 1. Comparison of key performance and characteristics of three types of underwater robots

Type of submersible	ROV Remotely Operated Unmanned Vehicle	AUV Cordless Underwater Robot	ARV Autonomous/Remotely Operated Underwater Robot
control method	Remote control by technicians via fiber optics, cables	Autonomous execution of tasks according to predefined procedures	Technology integration of ROV and AUV
specificities	Safe, flexible, long-lasting, and adaptable to different depths. But has limited movement range and high operation & maintenance needs.	Flexibility, autonomy, and a wide range of activities; however, range and mission scope are limited, and recovery is risky	Large range of activities, low dependence on the mother ship, combination of manual intervention and autonomous operation, high reliability and operational capability
Areas of application	Mainly used in offshore engineering, submarine cable laying, oil and gas field maintenance, wreck salvage, and other tasks that require high-precision operation.	Suitable for long-distance, wide-area autonomous exploration in ocean surveying & mapping, environmental monitoring, resource exploration, military reconnaissance, etc.	Combining the characteristics of ROV and AUV, it is used for deep-sea exploration, scientific research, underwater archaeology, and other missions that require flexible operation and autonomous navigation.

2.1 Remotely Operated Unmanned Vehicles

Remotely operated unmanned vehicles (ROV) are remotely controlled by technical operators through fiber optics, cables, etc. This technology dates to around the 1950s [3], with initial research focusing on military missions and scientific research. With the continuous progress of technology, especially after the 1970s, the exploitation of marine resources and the urgent needs in other fields have driven the rapid development of ROV technology. Its scope of application has gradually expanded from military and scientific research to a variety of fields, such as marine exploration, civil rescue, environmental monitoring, and underwater archaeology, and it has gradually formed a complete industrial chain. Unmanned submersibles are safe, flexible, reliable and can operate for a long time, with various specifications, and can adapt to different operational needs from shallow to the deep sea, but there are also problems such as the range of activities being limited by the length of cables, the operators need to have a high level of professionalism, and the equipment is complicated to operate and the maintenance cost is high. In recent years, thanks to breakthroughs in artificial intelligence technology, ROV autonomy has been significantly improved, such as the realization of autonomous navigation, obstacle avoidance, and mission planning, which opens up new possibilities for its application in underwater exploration and complex operations.

Guo and his team designed a multi-parameter water quality monitoring system based on the ROV submersible [4], which has a full-time automated detection function, can provide real-time feedback of the water body data, and can dive to different depths of the water layer to carry out accurate detection of a variety of water body data. With the help of this system, the investment of human and material resources in water body inspection has been greatly reduced, and the efficiency of resource utilization has been significantly improved, which effectively promotes the development of water body inspection work.

In the 1990s, China independently developed ROV for 600-metre-class life-saving dive support operations, as well as for offshore oil and gas development missions. In addition, China's life-saving force is equipped with several operational ROVs in the Hippocampus and Starfish series, which have more power, higher load capacity, and deeper dive depths. These ROVs have more powerful power, higher load capacity, and deeper dive depths, and the manipulators they carry are also very flexible, which can operate all kinds of underwater tools and carry out many complex underwater tasks in the underwater environment, thus fully meeting the diversified needs of life-saving rescue work in the extreme environment of the deep sea [5].

2.2 Cable-free Underwater Robots

A cableless underwater robot is a robot capable of performing underwater tasks autonomously, completing tasks on demand according to a predefined program. Since it does not need to be connected to a surface control station via cables and fiber optics, it has greater flexibility, autonomy, and range of motion than an ROV. However, the disadvantages are also obvious: the storage capacity of energy such as batteries in the robot is limited, so the actual endurance time and mission range are limited; the risk of recovery in the complex underwater environment is greater, and it may be difficult to recover. AUVs have important application value in the fields of marine scientific research, resource exploration, environmental monitoring, and military missions. With the development of technology, the performance and application range of AUVs will be further expanded to become an important tool for underwater missions.

Kokusai Denshin Denwa (KDD) International Communications has developed a cable-free autonomous underwater robot [6], AE1000, fitted with a variety of sensors such as water pressure, flow direction, cable detection sensors, and obstacle searching sonar, to maintain submarine fiber-optic cables and survey the environment of fiber-optic cable installations, navigating autonomously through artificial intelligence technology., Japan,

Stanford University robotics team developed a humanoid underwater archaeological robot Ocean One [7], the robot has two humanoid robotic arms that can be flexible to achieve the grasping action, but also can carry an independent power supply for independent operation, or by the surface of the mother ship power supply, and real-time data transmission and human-computer interaction. Its scope of operation covers the waters around Marseille, Corsica, and Cannes, France, and it is mainly responsible for detecting shipwrecks, aircraft wrecks, and submarines.

2.3 Autonomous/Remotely Operated Underwater Robots

Autonomous/remotely operated underwater vehicle (ARV) technology has been gradually developing in recent years. It is a combination of a ROV and an AUV. ARV does not need to be equipped with long-distance fiber optic cables and has a greater range of activities. At the same time, the surface support system of the submersible has been simplified, and the degree of dependence on the mother ship is reduced, which reduces all the requirements on the mother ship. It is not only able to provide immediate feedback of underwater data to the surface platform, allowing the surface operator to grasp the underwater situation in real-time, but the surface platform is also able to manually intervene and operate the submersible, to assist the operator in calibrating the operational status of the submersible, and to assist the submersible in completing the underwater mission successfully. This combination of manual intervention and autonomous operation greatly improves the reliability of the submersible, effectively enhances the operational capability and efficiency of the submersible and enables it to better cope with the complex and changeable underwater working environment [8]. ARV technology has an important application value because of its autonomy, and the combination of remote-controlled operations can become an important tool for underwater detection and mission execution.

The French Research Institute for Exploitation of the Sea (IFREMER) developed the HROV Ariane, which is mainly applied to the survey of special coastal terrain and the monitoring of biodiversity [9]. This robot weighs 1800 kg, with a maximum dive depth of up to 2500 m. It is equipped with high-definition cameras, hydroacoustic communicators, and manipulators, and it has two modes of operation: cable-controlled and autonomous. It can be deployed and recovered with the help of an ordinary ship. In remote-controlled (ROV) mode, it relies on an optical fiber connected to the mother ship to achieve real-time data transmission; while in autonomous (AUV) mode, it relies on hydroacoustic communication to transmit the collected data to the surface.

The Nereus HROV can change its mode of operation on demand before launch. Poseidon is capable of full-depth dives and is primarily used for Earth and life exploration research, and on 31 May 2009, it completed an exploration mission to the Marianas Trench [10].

3 Key Technologies and Challenges

In the field of underwater operations, robots face a very complex environment, including non-linear changes in water pressure with depth, turbulence interference in the water column, complex underwater geomorphology, and variable water quality. For robots to replace humans to work efficiently and reliably, they must rely on the synergistic development and breakthroughs of a series of core technologies, such as power and control systems, positioning and navigation systems, autonomous cruise technology, vision processing and communication, and multi-sensor fusion.

3.1 Positioning and Navigation Systems

Underwater robot localization and navigation techniques are key to ensure that they perform their tasks accurately in underwater environments. There are mainly visual navigation, acoustic localization, instrumented sensor, and multi-sensor data fusion navigation [11], waypoint projection, signal-based navigation, and map-matching navigation [12]. The development of underwater positioning and navigation technology to improve the accuracy and reliability of underwater positioning will further enhance the robot's mission execution capability.

Underwater terrain-aided navigation (TAN) can provide precise navigation for underwater vehicles, and the technology is independent and efficient, which has attracted much attention in the field of underwater navigation. The TAN process takes advantage of various matching algorithms, such as terrain correlation, filtering, and graphic optimization, and the terrain data is collected and analyzed by different sensors [12]. The system focuses on four main modules: terrain map modeling, terrain matching region selection, high-precision matching algorithm, and multi-sensor information fusion algorithm. Ding and Cheng proposed a combined matching algorithm of coarse matching and contour-based fine matching with higher accuracy and robustness [13].

A combined navigation system based on multi-sensor fusion can effectively improve navigation accuracy, Mu's team proposed a combined navigation algorithm: when the robot is working on the water surface where GPS position is available, the navigation system uses an adaptive error-tolerant filter to smooth the GPS trajectory and corrects the processed position information for the inertial navigation system [14]. If not in that environment, Variable Bayes (VB) is used to estimate the Doppler Velocity Log (DVL) measurement error covariance for the INS/DVL integration system, and finally, the altitude error is corrected normally by the Pressure Sensor (PS), which greatly improves the navigation accuracy and robustness against measurement uncertainty.

3.2 Autonomous Cruise Technology

Autonomous cruise technology for underwater robots refers to the technology that allows robots to autonomously plan their paths, autonomously avoid obstacles, and complete tasks without human intervention. This technology is inextricably linked to navigation and positioning technology and at the same time integrates several technologies such as path planning, autonomous obstacle avoidance, autonomous control, and artificial intelligence, which can ensure that the robot efficiently completes the task in complex environments.

Ricardo Café et al. designed an intelligent obstacle avoidance system based on the principle of triggering an emergency system through a potential collision with an obstacle or many tethered cable forces [15]. A new obstacle avoidance method is also proposed that combines the BK product of fuzzy relations and potential field techniques. In addition, a cable model is set up to simulate the forces exerted on the robot, and when the cable forces exceed a predefined threshold, the emergency system activates and takes measures to prevent potential collisions, which greatly improves the safety of underwater robots.

Xing proposed a complex motion planning algorithm integrating deep reinforcement learning (DRL) and an improved artificial potential field (IAPF) [16]. The algorithm overcomes the traditional active filter problem with the help of remote sensing information and integrates it with the traveler problem to reach the optimal path cruising; by combining DRL and multi-source data optimization, it achieves the minimization of the energy consumption at all target points; the use of inertial sensors to refine the trajectory ensures the smooth navigation and precise positioning, which guarantees the energy efficiency and also achieves the optimal solution of path planning with high security.

3.3 Energy and Power Systems

In the operation system of underwater robots, the energy reserve and energy supply mode are the key factors determining their endurance. Currently, the main types of energy applied to underwater robots include electric energy, solar energy, and nuclear energy. Among them, electric energy is the most widely used due to its convenient conversion and rapid response. As a clean energy source, solar energy is still a possible choice due to its sustainable accessibility, although it is limited by light conditions; nuclear energy, with its high energy density, is mostly used in the military field and is suitable for long-cycle and long-distance execution of underwater tasks. The power system, on the other hand, is the core component for the operation of underwater robots, including several subsystems such as propulsion, power distribution control, energy management, and thermal management. Sufficient endurance enables the robot to significantly improve efficiency and mission integrity.

To improve charging efficiency, Zhang and his team proposed a lightweight general-purpose variable toroidal magnetic coupler to address the shortcomings of wireless power transmission instability [17]. They optimized the system topology and the structure of the magnetic coupler, which not only made it lightweight but also effectively improved the charging efficiency.

For better battery thermal management, Li et al. proposed a novel and efficient battery liquid cooling scheme [18]. The bionic wave cooling channel technology is introduced in the thermal management of underwater robotic energy systems. They constructed a three-dimensional heat dissipation model and found that enhancing the coolant mass flow rate is the key to reducing the maximum battery temperature and enhancing the temperature uniformity. Although the coolant inlet direction has a small effect on the maximum battery temperature, it can significantly enhance the temperature uniformity. On the discharge strategy, under the requirement of robot cruising, alternating low and high-rate discharges can avoid overheating and shortening the life of the battery, which effectively improves the energy utilization efficiency and guarantees the range.

4 Key Challenges and Outlook

In the field of marine resource development, scientific exploration, and other areas, underwater robotics technology shows great potential but also faces multiple challenges.

(1) From the point of view of environmental adaptability, the high pressure, low temperature, and complex flow field conditions in the deep-sea region, the robot's structural materials and sealing technology put forward stringent requirements, need to have excellent pressure resistance, low-temperature resistance, and corrosion resistance.

(2) In terms of energy supply, the energy density and endurance of the current battery technology are limited, and the development of high-performance batteries and intelligent energy management systems to ensure the stable operation of robots for a long time has become the key to breakthroughs.

(3) At the level of communication and navigation, the underwater environment has strong attenuation characteristics for electromagnetic waves and light waves, GPS and other positioning signals are difficult to penetrate the water body, and traditional acoustic communication technology also exists in the low transmission rate, susceptible to interference and other problems, how to achieve efficient and reliable underwater communication and precise navigation, and the development of a high-precision underwater integrated navigation system [10], is an important research direction in this field.

(4) In terms of autonomous decision-making and control, the complex and changing environment underwater requires robots to have highly intelligent autonomous positioning, environment sensing, and modeling capabilities to achieve accurate decision-making and mission planning.

In addition, there is no uniformity in the technical standards of various countries, coupled with the high cost of research and development, manufacturing, and maintenance of underwater robots, which to a certain extent restricts its large-scale promotion and application.

In summary, underwater robotics technology, as a complex technology of multidisciplinary cross-fertilization, requires people's collaborative innovation to achieve substantial breakthroughs in the technology and promote its wider application.

5 Conclusion

This study adopts the method of literature review and case study analysis to study the classification of technology, the current situation, research progress, and applications of underwater robotics. The research findings indicate that the mainstream product categories in the underwater vehicle market, including ROV, AUV, and the newly emerging ARV, have experienced rapid development in recent years. These products play a pivotal role in numerous fields due to their distinct technical advantages and application scenarios.

However, from a practical point of view, underwater robots in the level of intelligence and endurance and other key performance indicators, there is still much room for improvement. Intelligent, although the robot has a certain degree of autonomy, in the face of the complex and changing underwater environment, the accuracy and adaptability of its intelligent decision-making still needs to be improved; endurance, limited by the bottleneck of the energy density of the existing battery technology, underwater robots long time, long-distance operation ability is constrained.

Underwater robots are accelerating toward intelligence and autonomy, and the integration of interdisciplinary technologies has become the core driving force to promote technological innovation and development. At the technical level, with the deep integration of artificial intelligence technology, the autonomous navigation and obstacle avoidance algorithms of underwater robots have been optimized, which significantly improves the autonomous decision-making ability of underwater robots in complex environments. The fusion of 5G/6G and acoustic communication technology lays the foundation for the realization of high-speed and stable communication links underwater; the breakthroughs in high-pressure and low-temperature-resistant composites have brought innovations to structural design. The hardware performance of the power system has been improved to optimize the operational efficiency and stability of the robot. The emerging battery technology has alleviated the bottleneck of the traditional battery. The bionic structure design has optimized the mobility of the robot, and the multi-robot cluster collaboration has improved the operational efficiency. In the field of application, underwater robots are used in deep-sea resource development, marine energy development, ecological monitoring, and protection of the deep integration with the marine economy. In the future, the development direction of underwater robotics is as follows: 1) continue to deepen the interdisciplinary technology integration, and breakthroughs in existing technology bottlenecks; 2) governments to increase policy support, the development of special planning, the establishment of scientific research funds and to promote cooperation between the industry, academia and research; 3) the establishment of a sound technical standard system, accelerate the layout of the global market, to expand a wider range of markets.

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