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Analysis of Development Trends in Underwater Robotics

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Abstract: Since the 1950s, underwater robotics has evolved from exclusive military applications to broad uses in marine science, resource exploration, and environmental monitoring. This paper reviews the development history of underwater robots, analyzes advancements in key technologies such as navigation and control, energy and power, communication, and materials, and discusses future trends in intelligence, modularization, networking, and miniaturization. These technological advancements and trends not only enhance the performance and adaptability of underwater robots but also provide vast prospects for their application in complex marine environments. By summarizing key technologies and development trends, this paper provides a reference for further research and application in underwater robotics technology.

Keywords: Underwater Robots; Autonomous Underwater Vehicles (AUVs); Remotely Operated Vehicles (ROVs); Communication Technology; Intelligent Modularization.

1. Development History of Underwater Robots

The development history of underwater robots is a journey filled with innovation and exploration[1], tracing its origins back to the 1950s. During that time, with the intensification of the Cold War and the rising strategic importance of the oceans, various countries began investing substantial resources in the development of underwater robots, primarily for military reconnaissance and seabed mapping.

As technology advanced, the functionality and application scope of underwater robots greatly expanded[2]. In the 1970s, with the rapid development of computer and sensor technologies, underwater robots began to possess more powerful data processing capabilities and environmental sensing abilities[3], enabling them to perform a wider variety of tasks in more complex environments.

Entering the 21st century, with the rapid advancements in artificial intelligence, unmanned systems, new materials, and other technologies, underwater robots encountered new development opportunities[4]. Robots from this period exhibit higher levels of intelligence and autonomous operational capabilities, able to independently complete complex tasks without human intervention. Additionally, breakthroughs in energy and power technologies have significantly enhanced the endurance and mobility of underwater robots. These advancements enable underwater robots to better adapt to various complex marine environments and meet more diverse application needs.

Today, underwater robots are widely used in marine scientific research, ocean resource exploration, marine environmental monitoring, and ocean engineering, playing an essential role in these fields.

Figure 1. Remotely Operated Vehicles (ROVs) A

Figure 2. Remotely Operated Vehicles (ROVs) **B**

2. Key Technologies of Underwater Robots

Underwater robots rely on a series of key technologies to perform various complex tasks efficiently and accurately. Here is a detailed introduction to these key technologies:

2.1. Navigation and Control Technology

Navigation and control technology are crucial for underwater robots as they determine the robot's positioning[5], path planning, and motion control in underwater environments. Commonly used navigation technologies for underwater robots include:

1) Inertial Navigation: Utilizes inertial sensors such as gyroscopes and accelerometers to measure the robot's angular velocity and acceleration, and integrates these measurements to obtain the robot's position and attitude information. However, due to error accumulation in inertial sensors, this method is often combined with other navigation methods.

2) Acoustic Navigation: Uses the propagation characteristics of sound waves underwater for navigation. Common acoustic navigation methods include Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL), which determine the robot's position by measuring the time difference or phase difference of sound waves from the transmitter to the receiver.

3) Visual Navigation: Employs cameras and other visual sensors to capture underwater environment information and uses image processing techniques for navigation and positioning. This method is suitable for well-lit, clear water conditions.

In terms of control technology, underwater robots typically adopt autonomous control strategies[6], including path planning, trajectory tracking, and attitude adjustment. These control strategies are designed based on the robot's motion model and environmental model to achieve efficient and stable control.

2.2. Energy and Power Technology

Energy and power technology determine the endurance and mobility of underwater robots. Commonly used energy types include:

1) Battery: Lithium-ion batteries and other chemical batteries are the most commonly used energy sources for underwater robots[7], offering high energy density, small size, and light weight. However, battery endurance is limited and requires regular replacement or recharging.

2) Fuel Cell: Generates electrical energy through chemical reactions, providing high energy conversion efficiency and zero pollution. However, fuel cells are costly and require carrying hydrogen or other fuels, increasing the robot's size and weight.

3) Nuclear Energy: As a high energy density source, nuclear energy can provide long endurance for underwater robots[8]. However, the use of nuclear energy involves radiation safety issues, requiring strict adherence to relevant regulations and standards.

In terms of propulsion technology, underwater robots commonly use electric propulsion[9], hydraulic propulsion, and jet propulsion. Electric propulsion offers simple structure and low noise, suitable for small underwater robots; hydraulic propulsion provides high thrust and fast response, suitable for large underwater robots; and jet propulsion offers high propulsion efficiency and strong adaptability, suitable for various types of underwater robots.

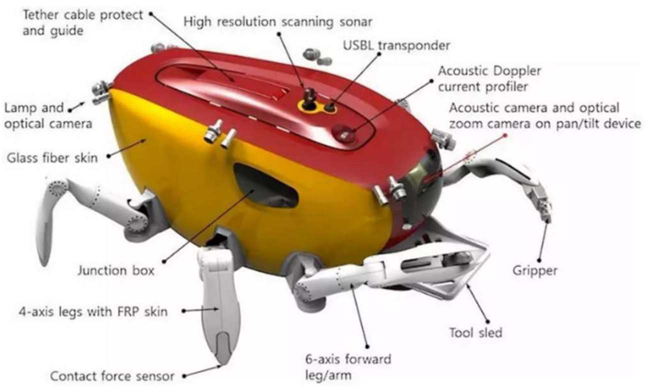

Figure 3. Korean Amphibious Robot

2.3. Communication Technology

Communication technology is essential for information exchange between underwater robots and the ground control center[10]. Due to the unique underwater environment, traditional wireless communication methods are not applicable, necessitating the use of special underwater communication technologies. Commonly used underwater communication technologies include:

1) Acoustic Communication: Utilizes the propagation characteristics of sound waves underwater for communication. Acoustic communication has the advantages of long transmission distance and strong anti-interference capability, but it has a low transmission rate and is affected by underwater noise and multipath effects[11].

2) Underwater Optical Fiber Communication: Uses optical fibers as the transmission medium for communication. Underwater optical fiber communication offers high transmission rates and strong anti-interference capability[12], but it is costly and requires the deployment of optical fiber cables.

To improve the reliability and efficiency of communication, researchers have developed some new communication technologies, such as communication technology based on underwater acoustic networks and communication technology based on quantum entanglement.

2.4. Materials and Technology

Due to the complexity and corrosiveness of underwater environments, the materials and technologies used in underwater robots must meet special requirements[13]. Currently, commonly used materials include stainless steel, titanium alloys, and composite materials, which have excellent corrosion resistance and strength. In terms of technology, underwater robots typically employ anti-corrosion techniques, sealing technologies, and waterproof technologies to ensure the stability and reliability of the robots in underwater environments.

With the continuous advancements in material science and manufacturing technology[14], future underwater robots will utilize lighter, stronger, and more corrosion-resistant materials along with more advanced manufacturing techniques to enhance their performance and lifespan.

Figure 4. Underwater Robots with Robotic Arms **A**

Figure 5. Underwater Robots with Robotic Arms **B**

3. Development Trends of Underwater Robots

As technology advances rapidly, underwater robot technology is experiencing unprecedented development opportunities. The future development trends will mainly be reflected in the following aspects:

3.1. Intelligentization

Intelligentization will be a crucial direction for the development of underwater robots. Leveraging artificial intelligence technology, underwater robots will be able to autonomously perceive, learn, and make decisions, enabling them to complete various complex tasks more intelligently.

1) Environmental Perception and Recognition: Through high-resolution sensors and advanced data processing algorithms, underwater robots can perceive their surroundings in real-time and accurately identify target objects.

2) Autonomous Planning and Decision-Making: Based on algorithms like deep learning, underwater robots can autonomously plan task paths and make real-time decisions based on environmental changes.

3) Collaborative Operations: Multiple underwater robots can achieve information sharing and collaborative operations, improving task execution efficiency.

3.2. Modularization

Modular design will become a key principle in the design of underwater robots. Modular design will allow underwater robots to have higher versatility and scalability to meet different task requirements.

1) Quick Assembly and Disassembly: Through standardized module interfaces, underwater robots can be quickly assembled and disassembled, improving maintenance efficiency.

2) Function Customization: Suitable modules can be selected and combined based on different task requirements to achieve function customization.

3) Scalability: With the development of technology, new functional modules can be continuously added to the existing system to achieve functional upgrades.

3.3. Networking

Networking will be an important trend in the development of underwater robots. Through networked connections, underwater robots can exchange information and collaborate with ground control centers, other underwater robots, and satellites.

1) Remote Monitoring and Control: Ground control centers can monitor the status of underwater robots in real-time and perform remote control.

2) Real-Time Data Transmission: Underwater robots can transmit collected data to ground control centers in real-time, providing strong support for decision-making[15].

3) Collaborative Operations: Multiple underwater robots can achieve information sharing and collaborative operations, improving task execution efficiency.

3.4. Miniaturization

With the progress of material science and micro-nano technology, future underwater robots will move towards miniaturization. Miniaturization will make underwater robots lighter, more flexible, and better able to adapt to complex and changing marine environments.

1) Improved Stealth: Miniaturized designs make underwater robots harder to detect, enhancing their stealth capabilities.

2) Reduced Energy Consumption: Miniaturized designs result in lower energy consumption, extending endurance[16].

3) Adaptation to Complex Environments: Miniaturized designs allow underwater robots to better navigate narrow and complex marine environments.

Figure 6. Micro underwater robots

4. Conclusion

Underwater robotics technology has evolved from its initial military applications to widespread use in marine scientific research, resource exploration, environmental monitoring, and marine engineering. Through continuous innovation and breakthroughs in key technologies, underwater robots now possess capabilities for autonomous navigation, complex environment perception, and long-duration operation. In the future, underwater robots will play an increasingly significant role in marine resource development, environmental protection, and scientific research, providing robust technical support for human efforts to explore and protect the oceans.

In summary, the continuous development and innovation in underwater robotics technology will drive advancements in marine science and technology, meeting diverse application needs and bringing revolutionary changes to scientific research and practical applications in the marine domain.

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