Robotic fish: Opening a new era of underwater detection

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Escalating competition within aquatic environments, particularly in oceans, underscores the imperative for innovative solutions in underwater operations. These solutions necessitate the development of intelligent underwater equipment, with robotic fish emerging as a promising contender.[1] Leveraging advancements in robotics and artificial intelligence, robotic fish offer a suite of advantages that position them as transformative assets in underwater exploration and operations. Robotic fish are autonomous robots designed based on biomimetics principles that mimic the appearance of fish and can autonomously swim and perform specific tasks in water. The robot exhibits notable advantages, including high propulsion efficiency, robust maneuverability, effective concealment, low noise emission, and minimal environmental impact.[2] These attributes position robotic fish as viable substitutes for manual long-term operations in heavily polluted, high-risk, and low-visibility waters, thereby addressing the vulnerabilities inherent in traditional propeller drives. Consequently, research into robotic fish has gained significant attention among scholars globally,[3] as shown in Figure 1.

The streamlined body structure of robotic fish facilitates propulsion through tail oscillation or body undulation, endowing them with high maneuverability and the capability for agile navigation even in narrow passages.[4] The current mainstream dynamic mode of robotic fish is to use the propulsion provided by the caudal fin drive and the assistance of the pectoral fins to achieve straight, turning, and diving movements. Through diversified transmission structures, intelligent materials, and modular design, the motion characteristics of biological fish can be better simulated. By utilizing robust and highly adaptable control algorithms, the performance indicators of robotic fish can meet different task requirements. Furthermore, leveraging biomimetic characteristics reminiscent of fish, robotic fish demonstrate considerable potential applications in resource exploration, water-quality monitoring, fault detection, and military reconnaissance missions.

Robotic fish can illuminate the mysteries of the ocean's depths with their distinctive design and performance capabilities. The Massachusetts Institute of Technology introduced SoFi, which weighs 1.6 kg and can be maneuvered entirely by its undulating tail for propulsion, turning, and diving. Its soft silicone rubber material enables swifter swimming compared to conventional "hard" robotic fish. During a dive test in Fiji's Rainbow Reef, SoFi maintained continuous operation for 40 min at a depth of 18 m, capturing captivating underwater footage. Similarly, Eidgenössische Technische Hochschule Zürich developed Belle, a robotic fish measuring 1 m in length and weighing 10 kg, equipped with two chambers propelled by water circulation. Belle is capable of collecting DNA samples from underwater flora and fauna, enriching marine biological exploration data. Drawing inspiration from the flexibility of rays, Zhejiang University designed a robotic fish measuring 0.22 m in body length and 0.28 m in wingspan, employing dielectric elastomer thin films as propulsion devices. This robot surveyed resources at a depth of 3,224 m in the South China Sea. It successfully operated at a depth of 10,900 m in the Mariana Trench, offering invaluable data for human deep-sea exploration.[5] Thus, the emergence of robotic fish significantly contributes to the protection of marine ecosystems, the exploration of marine resources, and efforts toward sustainable development.

With the rapid acceleration of industrialization and urbanization processes, water pollution is escalating. Traditional methods of water-quality monitoring face constraints in time, sampling points, and labor costs. However, robotic fish, augmented by sensors and other equipment, offer dynamic, remote, and long-term monitoring capabilities for water bodies. Beihang University developed a robotic fish for patrolling China's Taihu Lake, measuring 1.2 m in length and 0.5 m in height and weighing 40 kg, capable of maintaining a speed of 3.0 km/h for 20 h and transmitting real-time water quality data. It also has an advanced maneuvering control system enabling the setting of monitoring depths and operating trajectories, contributing to sustained and comprehensive water conservation efforts. With the aid of robotic fish, the area and density of cyanobacterial blooms in China's Taihu Lake decreased by 45.7% and 30.3%, respectively, in 2023 compared to previous years, reaching the best level since 2007. In managing the Thames River, the University of Essex deployed robotic fish for water-quality monitoring, measuring 0.5 m in length and 0.15 m in height, capable of operating for 24 h and equipped with various sensors and autonomous coordination capabilities. When detecting harmful substances in the water, a robotic fish can communicate this information with other units and alert researchers and environmental agencies. Furthermore, robotic fish developed by the Polytechnic University of Madrid and the University of Florence are utilized to track pH levels in aquaculture environments. Stakeholders can manage water quality parameters by leveraging data provided by these robots, thereby enhancing management decisions and improving aquaculture quality. These examples underscore that robotic fish have surmounted the constraints of traditional water-quality monitoring systems, significantly expanding monitoring capabilities and intensity.

In the modern industrial sector, robotic fish technology has emerged as a novel tool for fault detection, offering crucial support for ensuring industrial safety and enhancing production efficiency. The "Gulf of Mexico oil spill" incident inflicted severe damage on marine ecology, prompting Michigan State University to develop GRACE, a robotic fish measuring 0.65 m in length and 0.18 m in height and weighing 8 kg. Equipped with multiple sensors, positioning devices, and wireless communication equipment, GRACE can continuously monitor and track oil spills in key Gulf areas. With its gliding capabilities, GRACE operates effectively in harsh marine environments, augmenting monitoring efforts for underwater oil pipelines. Similarly, State Grid Tianjin Company designed a robotic fish for the internal inspection of large oil-immersed transformers. This robot boasts a 360° rotation capability, cruising at a speed of 0.04 m/s, and descending at 0.025 m/s, with a hover error $\leq$0.03 m. It also incorporates functions such as image recognition, spatial positioning, path tracking, and omnidirectional cruising, enhancing transformer operation and maintenance intelligence and supporting new power system construction. With robotic fish assistance, the Tianjin power grid observed a 15% year-on-year reduction in equipment failure rates in 2023, achieving a power supply reliability rate of 99.9931% and a power supply voltage qualification rate of 99.997%. Despite the remarkable milestones of robotic fish in industrial fault detection, challenges persist in terms of detection accuracy and equipment maintenance. Consequently, further enhancements of their engineering application value are warranted through the integration of artificial intelligence and data analytics methods.

The emergence of robotic fish as a novel type of unmanned submersible has ignited enthusiasm in the realm of military technology. The United States Navy's spy robotic fish, Silent NEMO, bears a resemblance to tuna. Measuring 1.5 m in length and weighing 45.3 kg, this robot can dive to depths of 91.4 m. Silent NEMO evades sonar tracking more effectively because it operates more quietly than miniature submarines due to its propulsion mechanism relying on tail oscillation rather than propellers. It can accurately identify and remove obstacles such as mines in environments with low visibility, ensuring safe passage. China has also achieved significant progress in robotic fish research, unveiling the NH-1, NH-2, and NH-3 submersibles weighing 180, 1,800, and 13,000 kg, respectively, with speeds of 17, 22, and 27 knots. These submersibles excel in underwater

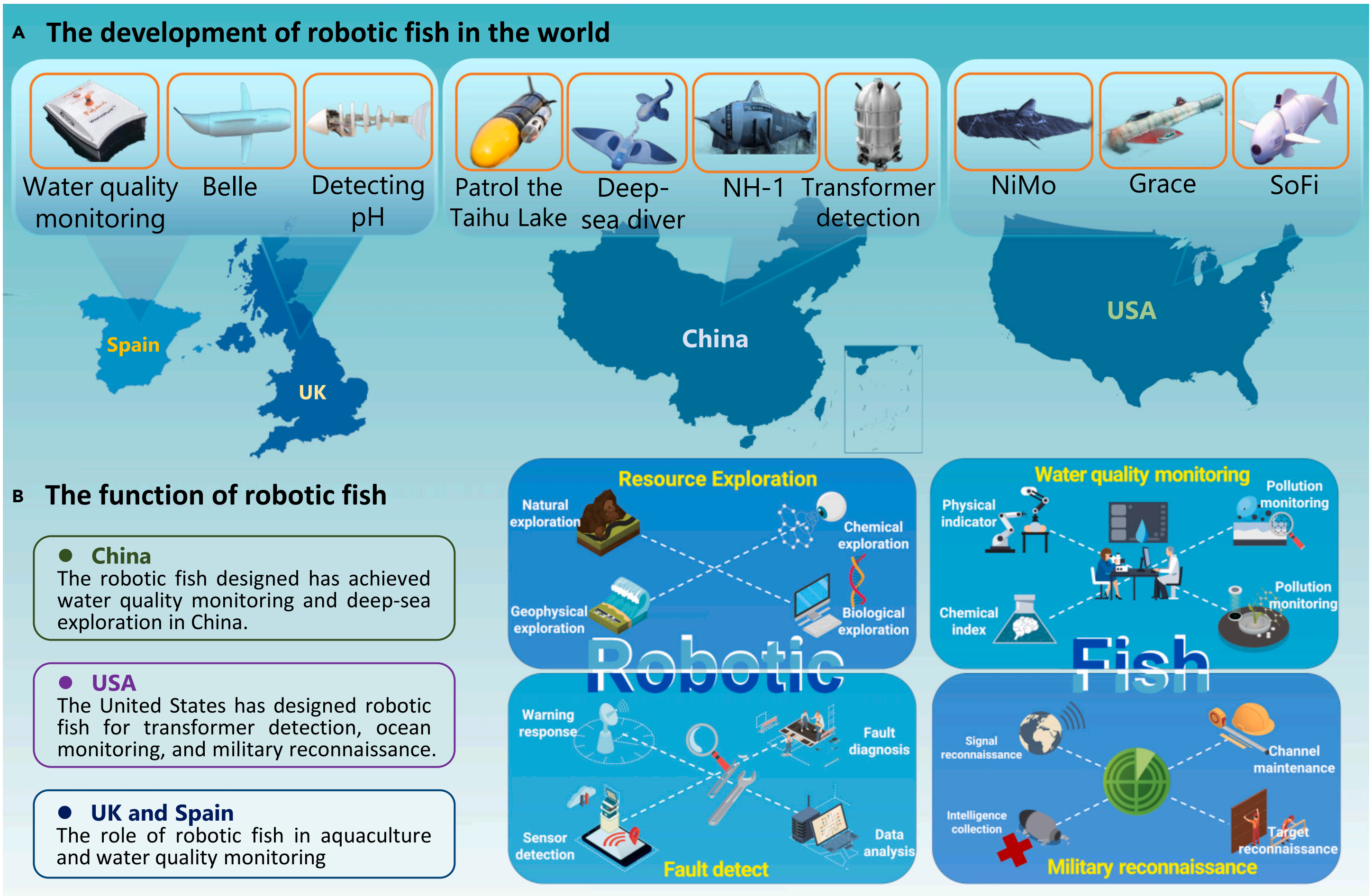

Figure 1. Development and application of robotic fish (A) Robotic fish have received extensive attention from scholars worldwide. (B) Advantages and application scope of robotic fish.

reconnaissance, torpedo deployment, and disrupting enemy communications. In the foreseeable future, robotic fish will greatly enhance the underwater combat capabilities and reconnaissance efficiency of military forces. However, robotic fish still need to overcome limitations in energy and control when confronted with complex battlefield environments and high-intensity combat tasks.

In summary, robotic fish have the potential to enhance researchers' capabilities to significantly explore underwater natural resources, understand marine ecosystems, conduct real-time monitoring of water quality, diagnose underwater equipment, and improve military combat capabilities. Despite significant achievements in the research of robotic fish, the challenges currently faced include how to control robots to achieve precise motion in complex water bodies, ensure long-term endurance and energy efficiency, and reduce manufacturing costs to meet large-scale adoption. Looking ahead to the future, the integration of robotic fish and artificial intelligence will be the key to exploring technologies such as autonomous decision-making, collective coordination, and multimodal perception. By interacting with real organisms to study animal behavior and ecosystems, it will promote interdisciplinary technological integration and development, thereby advancing the development of ecological conservation and benefiting humanity.

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DECLARATION OF INTERESTS

The authors declare no competing interests.