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Robotic Fish: Tiny Ocean Cleaners Fighting Plastic Pollution

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Plastic pollution is a threat to aquatic ecosystems, with microplastics in water, sediments, and aquatic organisms and creating ecological and human-health concerns. Robotic fish and micro/nanorobots are emerging as tools for detecting, collecting, and monitoring plastic pollution through bio-inspired movement, adsorption, electrostatic attraction, filtration, and technologies. Beyond plastic removal, these systems can support water-quality monitoring, pollutant and harmful algal bloom detection, aquaculture management, biodiversity assessment, and underwater inspection. Despite advantages such as maneuverability and monitoring, challenges include limited battery life, collection capacity, cost, navigation, and communication. Technological development, combined with plastic reduction and waste management, is essential for healthier aquatic ecosystems.

Keywords: Robotic fish; Microplastics; Aquatic pollution; Environmental monitoring.

Introduction

Plastic pollution has become a serious threat to aquatic ecosystems, as larger plastic debris gradually breaks down into microplastics (<5 mm) and nanoplastics, which can remain in water, sediments and aquatic organisms for long periods. These tiny particles can be ingested by fish and other aquatic animals, potentially causing oxidative stress, inflammation, tissue damage and disturbances in normal biological functions, while their occurrence in seafood has also raised concerns about possible human exposure (Habumugisha *et al.*, 2024). Their small size, diverse shapes and chemical composition make microplastics particularly difficult to detect and remove using conventional methods, creating a need for innovative and sustainable technologies. In this context, robotic fish and micro/nanorobots are emerging as promising tools for aquatic pollution control because they can be designed to move through water, detect plastic particles, and facilitate their removal through mechanisms such as adsorption, electrostatic attraction and magnetic separation (Shen *et al.*, 2024). Recent research has demonstrated an algae-based self-propelled microrobot capable of removing nanoplastics from water, achieving about 83% removal efficiency within two hours under experimental conditions (Qi *et al.*, 2024). Although these technologies are still at the experimental and prototype stage, their ability to combine bio-inspired movement, advanced materials, sensors and autonomous operation offers an exciting future possibility for developing targeted "underwater cleaners" to help reduce microplastic pollution in rivers, lakes and coastal waters.

Understanding Plastic Pollution

Plastic pollution in aquatic environments originates from land-based sources such as improper waste disposal, urban runoff, wastewater discharge, and industrial activities, as well as marine sources including fishing gear, shipping and aquaculture. Large plastic items such as bottles, bags, fishing nets and packaging are known as macro plastics, whereas plastic particles smaller than 5 mm are classified as microplastics, which may also be produced directly as small particles or formed through the fragmentation of larger plastics. Both forms pose serious ecological threats like fish, marine mammals and seabirds may ingest or become entangled in plastic debris, while microplastics can accumulate in organisms and potentially interfere with feeding, growth, reproduction and physiological functions, coral reefs may also be affected through physical smothering, abrasion and interactions with plastic-associated pathogens and chemicals (Borrelle *et al.*, 2020).

What Are Robotic Fish?

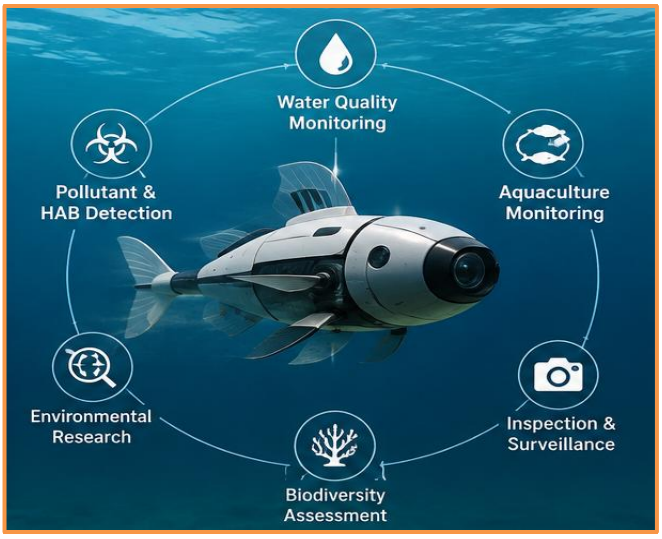
Robotic fish are bio-inspired autonomous or remotely controlled underwater robots designed to imitate the body shape, swimming motion, and maneuverability of real fish. Unlike conventional propeller-driven underwater vehicles, many robotic fish use flexible bodies, fins, or tail movements to generate propulsion, allowing them to move efficiently through complex aquatic environments. Their design is inspired by the natural swimming abilities of fish, which can provide high maneuverability, low-noise movement, and relatively low energy consumption. Modern robotic fish may incorporate soft or flexible materials, artificial muscles, flexible fins, cameras, chemical and environmental sensors, microcontrollers, batteries, and specialized propulsion systems. These features allow them not only to navigate underwater but also to detect and interact with pollutants. Depending on their design and purpose, robotic fish can be broadly classified into rigid-body robotic fish, flexible/soft robotic fish, fin-propelled robots, biohybrid robotic fish, and autonomous robotic fish equipped with sensing and navigation systems.

How Robotic Fish Capture Microplastics

Robotic fish can be designed to detect, collect, and monitor microplastic pollution while swimming through contaminated water. Their fish-like propulsion system enables them to move through shallow, confined, or sensitive aquatic habitats where conventional cleanup equipment may be difficult to operate. For microplastic collection, researchers have explored approaches involving electrostatic attraction, adsorption, filtration, and specialized collection surfaces. In electrostatic approaches, an electrically charged or functionalized collection surface can attract or retain small plastic particles from the surrounding water; adsorption-based materials can similarly capture particles on their surfaces. Once collected, the particles can be concentrated in an internal filter, mesh, sponge, or storage chamber, which can later be removed for analysis or disposal. At the same time, robotic fish can carry water-quality sensors to measure parameters such as temperature, pH, turbidity, dissolved oxygen, conductivity, and other indicators of aquatic pollution. After completing a cleaning mission, the robot can be guided back to a collection point, where its captured material can be removed, the collection unit cleaned or replaced, and the robot recharged and redeployed, making repeated monitoring and cleanup possible.

Applications Beyond Plastic Removal

a. **Water quality monitoring:** Measures temperature, pH, dissolved oxygen, turbidity and salinity in real time.
b. **Pollutant detection:** Helps identify chemical contaminants and other pollution hotspots.
c. **Harmful algal blooms:** Uses optical and chemical sensors to detect algae and associated toxins.
d. **Aquaculture monitoring:** Monitors Pond water quality, fish behaviour, biomass and farm conditions.
e. **Biodiversity assessment:** Captures images and environmental data to study aquatic organisms and habitats.



f. **Environmental research:** Collects continuous data for studying changes in aquatic ecosystems.
g. **Underwater inspection:** Examines fish cages, reefs, pipelines and other submerged structures.
h. **Surveillance:** Provides autonomous observation of difficult-to-access underwater areas.

Advantages of Robotic Fish

- Fish-like propulsion can reduce energy consumption and underwater disturbance compared with conventional propeller-driven systems.
- Small size and high manoeuvrability allow operation in narrow, shallow and complex underwater environments.
- Bio-inspired swimming can reduce noise and disturbance to fish and other aquatic organisms.
- Sensors can collect water-quality and environmental data repeatedly over long periods.
- Cameras and sensors can provide valuable information for pollution assessment, biodiversity studies and ecosystem research.

Limitations and Challenges

- Limited battery life
- Small collection capacity
- High manufacturing and maintenance costs
- Navigation challenges
- Limited communication

Conclusion

Robotic fish represent an exciting bio-inspired technology with the potential to support cleaner and healthier aquatic ecosystems by combining microplastic collection, environmental monitoring and underwater observation in a single platform. Although their small collection capacity, limited battery life, high costs and navigation challenges currently restrict large-scale application, they can serve as a complementary solution to conventional plastic-cleanup methods by targeting pollution hotspots and collecting valuable environmental data. However, technology alone cannot solve the global plastic pollution problem; reducing single-use plastic consumption, improving waste management, increasing recycling and preventing plastic from entering aquatic environments must remain the primary priorities. With advances in artificial intelligence, sensors, energy-efficient propulsion, autonomous navigation and coordinated robotic fleets, robotic fish could become valuable tools for monitoring and protecting aquatic ecosystems, contributing to a future of cleaner oceans and healthier marine life

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