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IoT-Based Underwater Robotics for Water Quality Monitoring in Aquaculture: A Survey

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Abstract. Water quality monitoring is a substantial part of aquaculture management, but with the increasing growth of human activities, environmental pollution has become particularly serious. In particular, the pollution of water bodies by radioactive substances is a hot topic today and it poses great potential that will seriously affect people's health. This paper presents a review on innovative solutions using IoT-based underwater robot clusters for monitoring water quality with a focus on detecting radioactive contaminants. Addressing the challenges of radioactive elements, particularly tritium, the solutions ensure safer waters, benefiting marine biodiversity, fisheries, and human health.

Keywords: underwater robot, IoT-based system, water quality monitoring

1 Introduction

Water quality is pivotal for the health of marine ecosystems, human well-being, and economies dependent on marine resources. Particularly concerning is the challenge of nuclear contamination, with isotopes like tritium emerging as prominent threats [19, 21]. This paper investigates into the burgeoning application of underwater robotic systems, underpinned by Internet of Things (IoT) technology, in aquaculture. The emphasis is on their potential for continuous water quality monitoring, offering a sustainable detection method while fostering enriched data interactions with researchers.

Recent years have witnessed a surge in the adoption of underwater robots commonly termed as Autonomous Underwater Vehicles (AUVs) [23, 13], Remotely Operated Vehicles (ROVs) [1], and when on the water's surface, Autonomous Surface Vehicles (ASVs) [24]—for water quality assessments. Equipped with an array of sensors, these underactuated robots possess the capability to monitor water quality metrics across diverse environments, be it oceans, rivers, or lakes.

While these robots can gauge a spectrum of parameters, from temperature and salinity to pollutants and specific microorganisms, there remains a gap in research [14]. Current literature often lacks systems that facilitate consistent and regular water quality monitoring [8]. Much of the extant work still leans on traditional, resource-intensive testing methods which are both costly and time-consuming [28, 27, 15, 16].

The paper starts by introducing various commonly used underwater robots, delineating their roles and functionalities within underwater monitoring ecosystems. This is followed by a deep dive into several mature underwater robot monitoring systems, aimed at imparting a comprehensive understanding of their overall structures to researchers. As we transition further, we critically evaluate the pros and cons inherent in the current generation of underwater robot monitoring systems. This analysis is presented to offer insights and references for impending research endeavors and technological enhancements.

2 Underwater Robots

In the field of underwater detection research, there are three efficient categories of underwater robots, namely AUVs [29, 25], ROVs [3, 18, 7] and ASVs [24, 6, 30]. Table 1 presents a list of 10 leading and widely recognized underwater robots, detailing their unique features. Table 2 offers a comprehensive comparison between AUVs, ROVs, and ASVs. In subsequent sections, a detailed analysis of these three underwater robots types is provided.

2.1 Autonomous underwater vehicles (AUVs)

An AUV, is a remarkable and highly advanced marine robotic system designed to operate autonomously beneath the water's surface. These vehicles have revolutionized underwater exploration and data collection by offering a self-contained platform capable of performing various tasks without direct human intervention. AUVs are equipped with a range of sensors and instruments that allow them to navigate, collect scientific data, survey the seabed, and even interact with their underwater environment. Their ability to work independently in challenging and often remote underwater environments has made AUVs invaluable in fields such as marine science, oceanography, environmental monitoring, underwater archaeology, and offshore industries. In this section, we will delve deeper into the capabilities, applications, and significance of AUVs in the world of underwater exploration and research.

The Deep C is an innovative AUV developed with the support of the Federal Ministry for Education and Research [10]. It is designed for inspection tasks in challenging underwater environments. The Deep C AUV is notable for its ability to operate for extended periods, achieve high speeds, and reach great depths. Additionally, it boasts exceptional maneuverability and navigation accuracy. The development of the Deep C AUV represents a significant technological

Table 1: Several underwater robots [5]

Underwater robot	Feature
Bluefin AUV	This robot can perform autonomous underwater navigation and object detection.
Peace 1 and Peace 2	These are the only pair of manned submersibles in the world that can perform collaborative underwater exploration.
Deep C	It is capable of operating at depths of up to 4000 meters and can work for 60 hours in the deep sea.
VICTOR 6000	This robot can acquire high-quality underwater optical images.
Autosub6000	This fully automatic submarine is equipped with batteries and sensors, enabling it to navigate independently.
Kaiko ROV	This robot is equipped with various underwater sensors and has been used for deep-sea exploration.
Qianlong and Haidou	These robots are equipped with sonar, cameras, and lights which are used for various underwater tasks at different depths.
Jiaolong and Fendouzhe	These robots are manned underwater submarines used for deep-sea exploration.
Orange Shark and Hai Ling	These robots can perform underwater environment exploration by installing various underwater sensors.
Bionic Dolphin	This robot can operate at depths of up to 800 meters.

Table 2: Underwater robots comparison

Feature	AUVs	ROVs	ASVs
Operational environment	Underwater	Underwater	Underwater
Mobility	Autonomous	Tethered	Autonomous
Energy Source	Autonomous	Tethered power, onboard battery	Batteries, solar systems, fossil energy
Communication	Acoustic communication, RF wireless	Real-time	Radio, satellite
Applications	Seabed survey, monitoring research	Close inspection, tasks near structures, monitoring research	Hydrologic monitoring, security
Deployment Duration	Extended periods	Periods are tether and energy limited	Varies, but most of them are long-duration
Cost	High initial, low operational	Moderate initial, low operational	Varies, typically moderate
Maintenance	Robustness	Worker safety	Collision avoidance
Special features	Deep diving, high autonomy	Precision tasks, high maneuverability	Weather adaptability, fast

advancement in the field of underwater robotics and offers a substantial financial advantage over conventional vehicles for underwater missions.

Bluefin AUV, a subsidiary of General Dynamics Mission Systems, specializes in the development of advanced underwater robotic systems. One of their notable products is the Bluefin-9 AUV, which is part of the Bluefin-9 and Bluefin-12 series. The Bluefin-9 AUV is a versatile and reliable underwater robot designed for a wide range of applications, from scientific research to defense and commercial tasks. Its modularity, autonomy, and adaptability make it a valuable tool for exploring and studying the underwater world.

In the research [20], the Bluefin AUV played a pivotal role in characterizing the influence of various oceanographic features on the redistribution of temperature, salinity, and density within the water column. Specifically, the study aimed to understand how phenomena like currents, tides, internal waves, strong shear, and vertical mixing impact the magnetic and electric fields within a particular oceanic region. The Bluefin AUV was deployed to gather essential data and provide insights into the complex interactions between these oceanographic factors and their effects on the physical properties of the water column, which, in turn, influence the magnetic and electric fields in the area under investigation.

2.2 Remotely operated vehicles (ROVs)

In [26] a water quality monitoring system was developed that utilizes a ROV to overcome the limitations of traditional stationary monitoring methods near hydropower facilities. This autonomous system incorporates an ROV equipped with a dissolved oxygen sensor, a tether management system for mobility, and a solar-powered docking platform for energy. A web-based interface provides real-time data visualization, overlaying readings on Google Earth. Preliminary tests at McNary Dam demonstrated the system's capability to sample water quality at various depths and locations, offering a more flexible and comprehensive approach to monitoring in challenging aquatic environments.

2.3 Autonomous surface vehicles (ASVs)

ASVs are gaining popularity worldwide, especially in the military and marine science sectors. Caccia's review [2] in 2006 highlighted that ASVs have been developed as prototypes for research and military purposes. Research-class ASVs tend to be slower but more stable catamaran-style vehicles, while military ASVs are typically faster and designed as monohulls [6].

ASVs are increasingly being utilized for marine applications, notably in hydrologic monitoring, maritime security, and offshore installation protection. Their deployment offers a trifecta of benefits: a significant reduction in personnel costs, enhanced safety by operating in potentially hazardous environments, and the flexibility to function under a wide range of weather conditions, even those deemed unfavorable [24]. While motion control remains a pivotal aspect of ASV research, encompassing dynamic positioning, trajectory tracking, and more.

3 Underwater monitoring system

In aquaculture, maintaining optimal water quality is crucial for the health and productivity of aquatic species. Adapting ROV-based system can revolutionize water quality monitoring in fish farms and other aquaculture setups. The ROV can be equipped with additional sensors to measure parameters critical for aquaculture, such as pH, salinity, ammonia, nitrate, and temperature. Its mobility allows for comprehensive sampling across different depths and locations within large ponds or cages, ensuring a holistic understanding of the water environment. The solar-powered docking platform ensures continuous monitoring without frequent manual intervention. The GUI can be tailored to provide aquaculture-specific insights, alerting farmers to any deviations from optimal conditions and suggesting corrective actions. This autonomous system can lead to more informed decision-making, optimizing fish health, growth rates, and overall yield in aquaculture operations.

The Mobile Water Quality Monitoring System (which is shown in Fig. 1) consists of a robot fish and a remote control terminal that communicate bidirectionally via Wi-Fi. The robot fish is designed to operate underwater, maintaining stability and agility, even against currents and waves. The process begins when the remote terminal instructs the robot fish. As the robot executes these actions, its sensors gather water quality data and send it to a database in real-time. This data is then processed and interpreted by control software on a host computer. Technicians use the processed data for analysis and decision-making. If pollutant levels exceed set standards, an automatic alert is triggered.

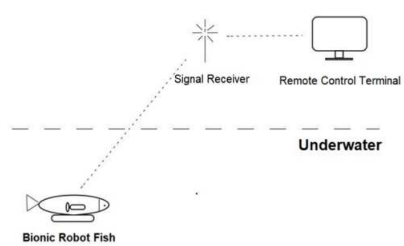

Fig. 1: Mobile Water Quality Monitoring System [11]

The water quality monitoring system (which is shown in Fig. 2) uses a ROV as its central component, equipped with a dissolved oxygen sensor for real-time water quality assessment. An automatic Tether Management System (TMS) ensures the ROV's free movement, while a solar-powered docking platform provides sustainable energy. Data visualization and real-time monitoring are facilitated through a web-based Graphical User Interface (GUI) that integrates readings onto Google Earth.

The Taxonomy water quality monitoring system (which is shown in Fig. 3) uses an array of sensors including pH, turbidity, temperature, conductivity,

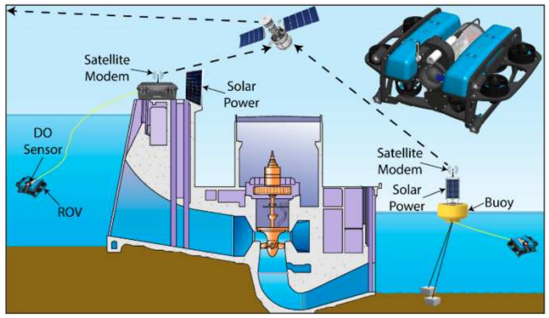

Fig. 2: Real-time and Autonomous Water Quality Monitoring System [26]

humidity, and more. A central core controller is pivotal to the system, where all sensors are linked. The controller oversees operations, retrieves data from the sensors, contrasts it with standard benchmarks, and then wirelessly conveys the data to relevant users or authorities. Enhancements in IoT technology have made these systems more intelligent, power-efficient, and user-friendly.

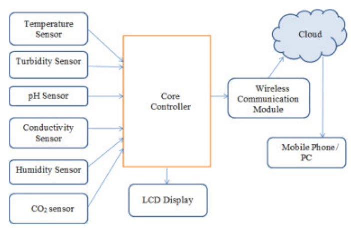

Fig. 3: Taxonomy water quality monitoring system [12]

Water quality monitoring systems (WQSN) using IoT System (which is shown in Fig. 4) is an automated freshwater pond for aquaculture, ensuring automatic maintenance, food feeding, and alert systems. Underwater sensors, part of the IoT framework, are set up to continuously monitor water quality parameters like pH, dissolved oxygen, nitrogen, ammonia, and temperature. The data from these sensors is sent to an Arduino/Raspberry-pi for analysis. Based on this analysis, necessary corrective actions, such as activating an aeration unit or switching on a motor for water level adjustments, are taken. Additionally, the system features an automatic fish feeder for consistent and optimal feeding. The end goal is to have a hands-free fish farming system with a water recycling feature.

The Hybrid Aerial/Underwater Robotic System (HAUCS) (whisch is shown in Fig. 5) is an innovative end-to-end framework designed to revolutionize pond-based farm operations. It integrates three main subsystems: aero-amphibious robotic sensing platforms that can operate both in-air and on-water, land-based infrastructure for automated charging and sensor cleaning, and a backend pro-

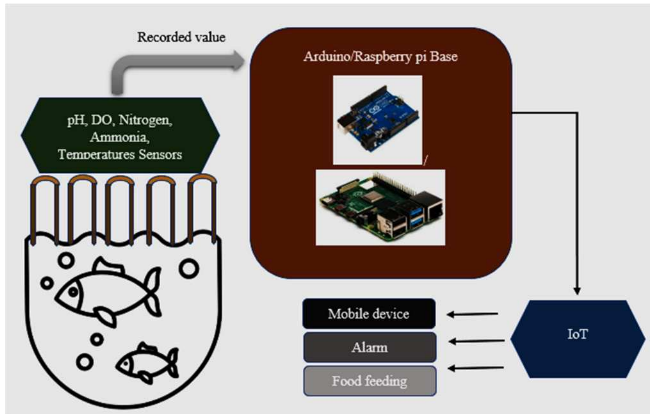

Fig. 4: WQMS IoT system [17]

cessing center equipped with a machine-learning-based water quality prediction model. By facilitating collaborative monitoring and decision-making, HAUCS aims to enhance the efficiency of aquaculture farms, making them more sustainable and resource-efficient. This system not only streamlines farm operations but also paves the way for the "Internet of Aquaculture," offering a scalable solution for farms of varying sizes.

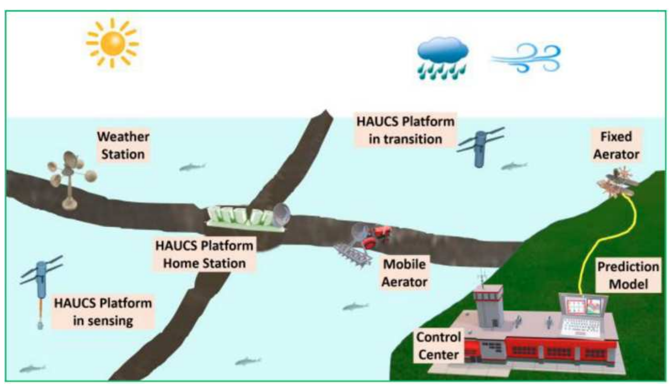

Fig. 5: HAUCS water quality monitoring system [22]

4 Challenges and Opportunities

The advent of underwater robotic systems offers promising avenues for monitoring water quality, with significant potential for advancing the field of aquaculture.

This section investigates the advantages of these systems, juxtaposed against the challenges they confront. As the evolution of underwater robotic systems continues, it is paramount to identify areas for breakthroughs to foster sustained progression and development.

4.1 Strengths

Long-Term Monitoring: Robots can remain deployed for extended periods, allowing for continuous or periodic data collection over time. IoT-based systems can continuously monitor water quality in real time. Traditional methods often require manual collection of water samples and subsequent laboratory testing, which can lead to delays in the testing process. Any discrepancies or inaccuracies can lead to false alarms or missed detections.

Efficiency Transmission: Many underwater robots have communication capabilities that allow them to transmit data in real-time to researchers or concerned authorities. ASVs have the capability for continuous or time-triggered communications, while there's a push towards event-triggered or self-triggered communications to reduce the communication burden and enhance operational flexibility.

Regional Conditions Challenge: AUVs can venture into areas that are difficult for humans to reach, such as deep-sea regions or hazardous environments. ASVs can function under a wide range of weather conditions, expanding the operational windows for marine tasks.

High Spatial Resolution: Instead of depending on a few point samples, AUVs can traverse vast regions, giving a detailed spatial overview of water quality. ASVs are allowed for coordinated control which means multiple ASVs can work together in a collaborative manner to achieve desired formation patterns or to cover larger areas efficiently.

4.2 Limitations

Energy Driven: Powering sensors and maintaining autonomous operation can be energy-intensive. This limits the duration for which some AUVs can be deployed. Designing and implementing a prototype model using nodes powered by solar panels and WSN technology can be complex.

Data Communication: Offshore wireless communication and satellite communication both face challenges related to climate and environmental conditions, resulting in unreliable connections and limited communication rates. Satellite communication, despite providing broader coverage, is associated with high operational costs and constrained bandwidth. While above water, data transmission is easier, but underwater, the communication becomes challenging due to water's attenuation of electromagnetic signals. Acoustic communication is often used, but it has limitations in terms of bandwidth and interference.

Robots Maintenance: Saltwater corrosion, biofouling, and the rugged underwater environment can pose maintenance challenges. Continuous operation might lead to biofouling or other environmental impacts, which can affect the robotics performance and require cleaning or maintenance.

Monitoring Accuracy: The system's accuracy needs to be validated by comparing the obtained results with probable values. For instance, the relationship between temperature with conductivity and pH was observed for samples from various water sources to ensure the system's accuracy. The lack of monitoring the radioactive substances is also the major problem in the environmental protection.

4.3 Future prospects

The rising concerns over nuclear pollution and the consequential effects of radioactive elements on our oceans and aquaculture have garnered significant attention in recent years, emerging as a societal focal point. In this context, it is imperative that underwater robotic monitoring systems are designed to encompass the detection and assessment of such pollutants. However, several challenges remain. Tritium, one of the many radioactive elements, proves particularly tenacious. Even after treatment with Japan's Advanced Processing System (ALPS), the complete removal of tritium remains elusive [4]. Additionally, the very environment these robots operate in presents another challenge. Nuclear-contaminated water, rich in high-energy particles, has the potential to jeopardize the robot's integrity, causing damage to its electronic components [9]. Addressing these challenges will be paramount as we navigate the future of underwater robotic monitoring.

5 Conclusion

The critical importance of water quality in marine ecosystems, human health, and marine-based economies underscores the necessity for continuous and precise monitoring. This paper investigated the integration of IoT-based underwater robotic systems in aquaculture, illuminating the potential of these technologies to revolutionize water quality monitoring. We analyzed various underwater robots, including AUVs, ROVs, and ASVs, showcasing their capabilities and applicability. As we continue to bridge the gap between traditional testing methods and the future of automated, continuous monitoring, it is evident that underwater robot systems will play an indispensable role. By harnessing the power of IoT and ongoing advancements in underwater robotics, we are poised to enhance the sustainability and accuracy of water quality monitoring in aquaculture, paving the way for a more informed and sustainable future. Finally, the risks posed by nuclear-contaminated water to the robots' electronic components highlight the need for advanced protective mechanisms.

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