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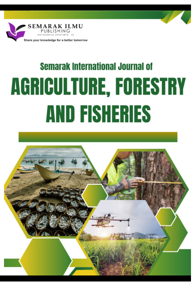

Sensing Technologies and Automation: Revolutionizing Aquaculture Towards Sustainability and Resilience

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ABSTRACT

Given the aquaculture industry's role at the forefront of addressing food security challenges facing the growing global population, the aquaculture sector also encounters various constraints that can impact its productivity, sustainability and resilience. These constraints include environmental issues, diseases, high reliance on the workforce and competition for water resources. This review provides an overview of the roles of sensing and automation technologies in revolutionizing aquaculture toward sustainability and resilience. Innovations in sensing and automation stand out as among the critical game-changing advancements that are transforming the way aquaculture industry operates. Intelligent sensing technologies offer major advantages in monitoring the environment, animal behaviour and growth, as well as early detection of diseases. By integrating advanced smart sensing devices, internet of things (IoT), artificial intelligence (AI) and automated response devices, aquaculture operations can be observed and managed remotely in real-time, leading to enhanced productivity, efficiency, resource utilization, environmental friendliness, reduced workforce dependency and competition over water. Through these revolutionary innovations, the aquaculture industry fosters a more sustainable and resilient future while contributing towards food security. Collaborative engagement of all stakeholders is crucial in realizing the full potential of sensing and automation innovations in aquaculture.

1. Introduction

As mankind is struggling with the challenges of food security, environmental degradation and climate change, aquaculture stands at the forefront in providing crucial source of protein to sustain the increasing human population. Aquaculture serves as a substitute seafood source for wild capture fisheries, helping to conserve marine ecosystems, alleviate pressure on depleted fish stocks and promote responsible stewardship of oceans towards a more sustainable and resilient future for

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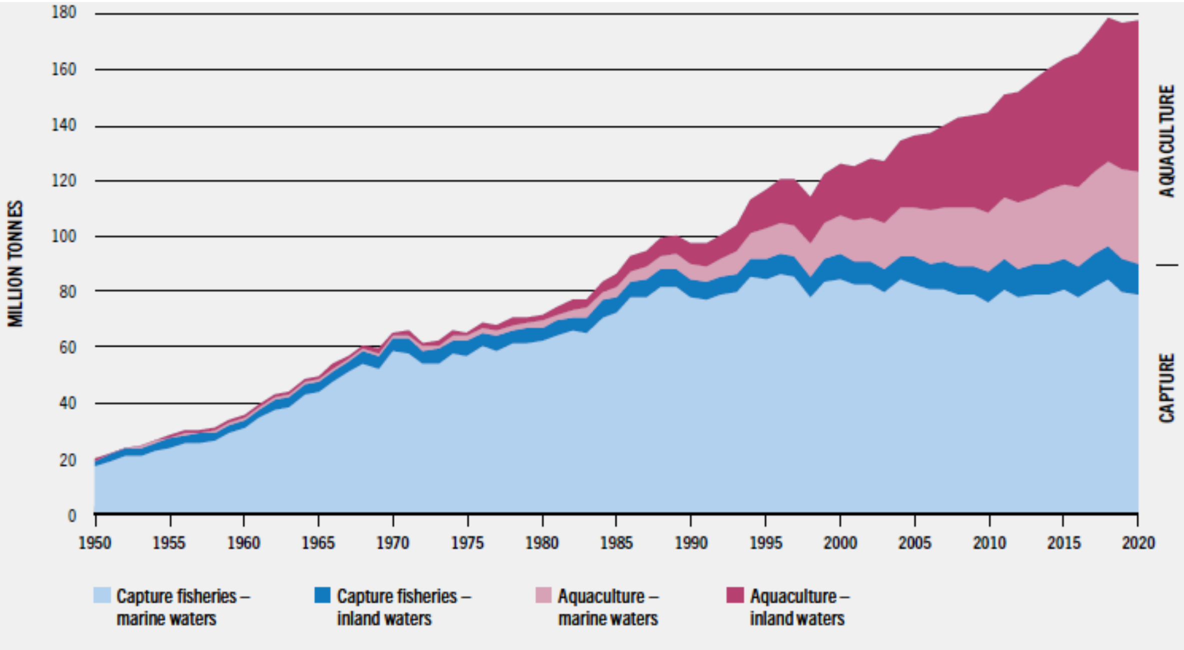
marine resources, and the communities that rely on them. Globally, aquaculture contributed nearly half of the world's fish and shellfish (Figure 1) in 2020 with 87.5 million tonnes (inland 54.4, marine 33.1) at USD 264.8 billion, compared to 90.3 million tonnes in fisheries (inland 11.5, marine 78.8), at a total production of 177.8 million tonnes (Table 1). Additionally, the algae aquaculture produced 35.1 million tonnes at USD 16.5 billion [1,2].



NOTES: Excluding aquatic mammals, crocodiles, alligators, caimans and algae. Data expressed in live weight equivalent.
SOURCE: FAO.

Fig. 1. World capture fisheries and aquaculture production [2]

Table 1
World fisheries and aquaculture production (FAO [1,2])

	1990s	2000s	2010s	2018	2019	2020
	Average per year *Million tonnes (live weight equivalent)*					
Production capture:						
Inland	7.1	9.3	11.3	12.0	12.1	11.5
Marine	81.9	81.6	79.8	84.4	80.1	78.8
Total capture	88.9	90.9	91.1	96.4	92.2	90.3
Aquaculture:						
Inland	12.6	25.6	44.7	51.3	53.3	54.4
Marine	9.2	17.9	26.8	30.8	31.9	33.1
Total aquaculture	21.8	43.4	71.5	82.1	85.2	87.5
Total world fisheries and aquaculture	110.7	134.3	162.6	178.5	177.4	177.8

Aquaculture involves a wide range of cultivation activities such as feeding, monitoring of animal health and growth, environmental and water quality parameters, disease control and prevention, harvesting, sales and marketing. Scientific researches and applications have led to development of new technologies that benefit aquaculture virtually in every aspect, and aided in its rapid global expansion. This has improved aquaculture operations, productivity and efficiency, increasing yields while reducing their negative impacts on the environment. Nevertheless, this burgeoning sector is not without its share of challenges and constraints, from environmental issues to diseases, as well as various other factors that pose significant threats to the sustainability and resilience of aquaculture industry worldwide.

2. Challenges and Constraints

2.1 Water Quality Changes

Optimal water quality is vital for maintaining high productivity and quality output in aquaculture. The culture species are more susceptible to health impacts in poor water quality condition. They are typically affected by variations in water quality parameters including temperature, dissolved oxygen (DO), pH, conductivity, turbidity and nutrient concentrations (ammonia, nitrate, nitrite and phosphate). Changes in water quality parameters will have a direct influence on the well-being of the animals, feeding behaviour, growth rate and the carrying capacities of the waterbody and farming systems [3]. For examples, water temperature affects both feeding rate and growth performance of fish [4]. Managing water quality in aquaculture can be difficult and often requires water sampling twice a day in the morning and afternoon. This process is laborious, and may not allow timely water treatment in cases of sudden changes in water quality.

2.2 Environmental Impact

Environmental degradation is one of the most pressing challenges and constraints facing aquaculture industry. Habitat destruction and pollution from leftover feed in ponds or tanks, and waste discharge from intensive farming practices can have detrimental effects on aquatic ecosystems. The impacts include eutrophication and habitat loss, as well as spread of non-native and potentially invasive species, all of which undermine the long-term sustainability of aquaculture operations and threaten biodiversity. Precision feeding in aquaculture is challenging as variability in environmental factors (e.g., water temperature, DO and climate changes) and feed quality can affect the feeding behaviour and metabolic rates of aquatic animals, making it difficult to maintain consistent feeding practices.

2.3 Diseases

Disease outbreaks represent a constant threat to aquaculture worldwide, causing significant economic losses and environmental damage. High stocking densities, deteriorated water quality and the globalization of trade increase the risk of disease transmission within and between aquaculture facilities, regionally and globally. Pathogens such as bacteria, viruses and parasites can spread rapidly, leading to mass mortalities and disruptions in production. Moreover, the misuses of antibiotics and other veterinary drugs also contribute to the development of antimicrobial resistance (AMR) and emergence of multidrug resistant organisms (MDROs), further complicating disease management efforts.

2.4 Labour Intensiveness

Traditionally, aquaculture operations often require a significant labor force to perform routine tasks such as feeding, monitoring, maintenance and harvesting. Monitoring animal health status and behaviour, immune response and water quality parameters are important for effective health management in aquaculture. The workloads of these laborious tasks, however, can be burdensome and overwhelming due to their demanding nature. This is especially true when there is a shortage of skilled labor, which often leads to compromise of effectiveness of health management system.

2.5 Water Usage Competition

Aquaculture relies heavily on clean water for farming. Competition with other industrial and human activities for water resources poses significant challenges to water utilization in aquaculture, particularly freshwater use in the regions already facing water stress. On the other hand, droughts due to climate change further exacerbate competition for water use. Recirculating aquaculture systems (RAS) is increasingly needed to reduce water abstraction from natural source such as rivers and coastal waters and to minimize environmental pollution by waste discharge. However, water quality in RAS also needs to be monitored to ensure that the system is working efficiently and optimally.

3. Sensing and Automation Technologies

3.1 Water Quality Monitoring

Traditionally, water quality monitoring involves measuring some parameters on-site using portable device, while some require laboratory analysis because of the need for specialized equipment, techniques or test kits. Depending on how well a farm is equipped with portable meters, on-site water quality measurements may include physical parameters such as water temperature, conductivity, turbidity and total dissolved solids (TDS); chemical parameters such as pH, oxidation-reduction potential (ORP), DO and salinity using single or multi-sensor meters. Some more advanced device such as the ProQuatro handheld multiparameter meter (YSI, USA) has the option of measuring additional chemical parameters such as ammonium (NH_4^+), nitrate (NO_3^-) and chloride (Cl^-) using ion-selective electrodes (ISE). On the other hand, biological parameters such as bacteria (e.g., total bacterial and vibrio counts), algae and viruses will require laboratory analyses. Although on-site measurements provide immediate data that can guide real-time decision-making, conducting routine monitoring from pond to pond or tank to tank on a large farm is rather laborious and time-consuming, and is likely to delay the final decision on the corrective measures. In this context, IoT-networked sensors will allow remote monitoring and supervision, visualization (if IP cameras are installed) and control using via mobile devices or computer terminal. If coupled with big data and AI-based data analyses, smart corrective measures can be automated at the farm level, and thus enhances the farm management efficiency amid constantly evolving on-farm conditions. Overall, the use of technologies such as smartphones, data mining, AI, big data, block chain, drones and cameras in aquaculture has significantly enhanced data collection, processing, analysis, storage, retrieval and reporting with speed and accuracy [5].

3.2 Environmental Impact Monitoring

Managing animal waste and uneaten food in aquaculture is essential for minimizing environmental impact and optimizing production. Overfeeding is a main reason for certain issues in fish farming [6] due to higher levels of nitrogen and phosphorus in the water. Additionally, too much inorganic nitrogen can cause acidification in freshwater ecosystems, adversely affecting the survival, growth and reproduction of aquatic life. It is vital to observe the behaviour of fish during feeding. Hungry fish typically rush to the feeding area to eat. Therefore, an automatic feeding system can use this behaviour as indicator to determine the best time to provide food [7]. However, when there is too much feed, the fish may behave as if no food is present, and allow them to sink to the bottom, causing pollution to the water and bottom. Improving the accuracy of feeding is therefore imperative. Efficiently integrating these factors could greatly benefit this process. Big data analytics, multi-sensor and computer vision technologies contribute to the data flow for fish feeding in aquaculture. Various methods can be combined with feed intake models at different levels of information fusion. On the other hand, the data flow of waste management systems in aquaculture follows these steps: at the first level of fusion, computer vision and signal/noise detection sensors are employed for pellet detection, solid waste assessment and dissolved oxygen measurements; at the second level of fusion, modelling techniques are applied based on different fusion levels [8].

Feed consumption and optimal animal are vital for sustainable production in aquaculture. Developing an accurate feeding model that promotes the most optimal growth of animal is a challenging task, which requires information fusion at the decision level. There is no universal model that suits all requirements due to the diverse environments and behaviours of aquatic animals [9].

3.3 Disease Monitoring and Diagnosis

Monitoring and managing the physical health of a large numbers of aquaculture animals that constantly swim and move are more complicated compared to domestic animals on land. In recent years, researchers and aquaculture experts have endeavored to enhance the diagnosis and treatment of fish diseases. Unfortunately, outbreaks still occur due to misdiagnosis, improper treatment or emergence of new diseases. As one of the most significant factors affecting sustainable aquaculture development, diseases may often manifest in different forms in different species. The diverse symptoms exhibited by individuals of different species with the same disease underscore the importance of species classification for accurate diagnosis.

On the other hand, some diseases also share common symptoms and clinical signs, posing a significant challenge to accurate diagnosis. Diagnosis methods such as flow cytometry (FCM) and polymerase chain reaction (PCR) offer fast and sensitive ways to detect bacteria [10-12]. Various biosensors have been developed to detect known aquatic bacterial and viral pathogens. For instances, quartz crystal microbalance (QCM) for viral hemorrhagic septicemia (VHS) [13], gold-nanoparticle based electrochemical DNA sensor for *Aphanomyces invadans* [14], lateral flow with gold nanoparticle for nervous necrosis virus [15], microcantilever sensor [16,17] and amperometric sensor [18] for *Vibrio cholerae* 01, potentiometric sensor using magnetic beads for *Vibrio alginolyticus* [19] and surface plasmon resonance (SPR) spectroscopy for *Vibrio parahaemolyticus* [20]. These sensors provide valuable contribution to the well-being of farmed animals and help in the comprehension of animal-disease-environment dynamics. Disease diagnosis in aquaculture using Big Data relies on various technologies and methods, including image comparison and biosensor techniques for real-time monitoring, as well as expert system analysis followed by fusion at different levels [21]. When integrated with IoT, diagnostic biosensors will allow remote sensing of aquaculture diseases, facilitating early detection of diseases and intervention to minimize losses.

3.4 Easing Labour Intensity

3.4.1 Animal behaviour monitoring

Manual observation and scoring of target behaviours of farmed species in aquaculture are time-consuming, labor-intensive and unstandardized [22]. In this context, various technologies including underwater motion capture have thus been integrated into aquaculture for monitoring purposes. Underwater video motion capture not only can monitor and track animal behaviours and feeding patterns but also assists in counting and provides insights into water quality by observing changes in water clarity, as well as the presence of debris or pollutants. Monitoring by motion capture along with tracking algorithms, deep learning and IoT, can be used to trigger alerts to the farm management to take immediate corrective actions to circumvent the problems encountered. Also referred as mo-cap or mocap, motion capture is a movement analysis technology using digital tracking and recording of movements of objects or living beings [23]. It is a technology adaptable for a wide range of applications in today's world, for examples, in entertainment, sports, healthcare and scientific research. It is also used in digital preservation of intangible cultural heritage, such as cultural dances [24-26], as well as in the study of human and animal behaviours.

Over the last twenty years, action sport cameras (ASC) have greatly improved in image quality and speed, while their prices have remained relatively stable. This has made them suitable for a wide range of applications including sports and athletic performance evaluation [27,28]. More recently, machine vision camera (MVC), although more expensive than ASC, has been utilized for motion analysis for more optimal functionalities. It is the recommended type of camera for 3D motion analysis software such as MaxTRAQ of Innovision Systems [29]. An MVC is typically employed in industrial environments using direct interaction with a computer or robot controller. These cameras can conduct image processing on their own, leading to lower energy consumption and faster data transfer [29].

3.5 Alleviating Water Competition

Water is essential for maintaining the aquatic environment in which aquaculture animals are raised. Water usage constitutes a significant cost factor in aquaculture, including the costs of water abstraction, filtration, treatment, quality monitoring and control. Water quality not only directly affects the health of aquatic animals but also their growth. Regular water exchange is an important management practice in aquaculture. It involves the use of significant volumes of water especially in intensive aquaculture systems, thus incurring substantial operational costs. Water exchange helps maintain water quality by replenishing oxygen levels, reducing buildup of toxic waste products such as ammonia and nitrogen compounds excreted by animals and preventing accumulation of excess nutrients that can lead to water pollution and harm to the aquatic life and ecosystem.

Improving and optimizing water utilization efficiency to reduce water usage are important goals in sustainable aquaculture practices. Competition for water between aquaculture and other industries can be reduced by technologies such as recirculating aquaculture systems (RAS), aquaponics and biofloc (BF). RAS and aquaponics minimize water usage by continuously reusing filtered water with minimal top-up, while BF converts waste products into useful biomass within closed systems. However, these technologies are not fool-proof. Careful monitoring of water quality parameters is necessary to prevent the systems from running into failure due to operational errors such as overfeeding, overstocking and maintenance shortfall. In this context, IoT based real-time water quality sensing technologies enable early intervention as soon as signs of deterioration are detected. On the other hand, optimizing feeding practices not only reduces feed wastage, but also alleviates burden on water self-purification and filtration systems, as well as the need for water replacement. Overfeeding leads to excess waste, accelerating water quality degradation. Sensing-driven automated feeding can significantly enhance feeding efficiency in this context.

The advance in information and communication technologies (ICT) and the emergence of compact and affordable sensor technologies have made it feasible to perform simultaneous monitoring of multiple parameters *via* wireless sensor networks (WSNs) [4]. A WSN basically consists of sensor nodes and a base station [30], where each node monitors defined parameters using its sensing and data transmission capabilities. The base station serves as a gateway to provide connectivity to all nodes, enabling data transfer and remote management of nodes. WSNs use low-power consumption standards such as GSM and Wi-Fi [30], Zigbee (IEEE 802.15.4-based) [31] and Bluetooth [32] for data transmission and communication. Overall, WSNs offer simple and cost-effective solutions for remote real-time monitoring with minimal human intervention and have become an integral part of Water Quality Monitoring (WQM) systems. Water management is indeed the primary domain where IoT and AI find extensive application (Table 2). Besides AI, the use of other technologies such as smartphones, data mining, Big Data, block chain, drones and camera in aquaculture has greatly enhanced data collection, storage, analysis, processing, retrieval and reporting capabilities [8].

Table 2
Some of the providers for digital and intelligence technologies used in aquaculture or potentially used in aquaculture

Companies	Technologies
Robotfish (http://www.qdlbf.com/)	Marine sensors, marine IoT, marine Big Data, underwater robots for various marine applications including aquaculture
Innovasea (https://www.innovasea.com/)	Aquaculture intelligence
Blueye (https://www.blueyerobotics.com/)	Underwater ROV for various industries including aquaculture (fish pen inspection)
Avetics (https://www.avetics.com/)	Comprehensive drone services including underwater ROV for various industrial applications
SeaDrone (https://seadronepro.com/)	Underwater inspection robots
Apium Swarm Robotics (http://apium.com/)	Swarm robots

4. Conclusions

The advancements of sensing and automation technologies in aquaculture industry signify an essential move towards sustainability and resilience. These advancements help optimize resource utilization, enhance production efficiency and mitigate environmental impacts. By adopting these revolutionary innovations, aquaculture industry not only meets seafood demands but also fosters a more sustainable and resilient future. Collaborative efforts of all stakeholders including the industry, governance bodies, technology developers and providers are vital to unlocking the full potential of these innovations and ensuring sustainability and resilience for aquaculture.

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