

Intelligent aquaculture

1 | INTRODUCTION

Fishery and aquaculture products are important sources of protein, providing food and income for hundreds of millions of people worldwide. Global aquaculture production has grown dramatically in the past 50 years, with total fish production from aquaculture reaching a record high of 82 million tons in 2018. In the development of aquaculture, traditional production models have played an important role in the rapid growth of aquatic product output. However, as consumption level and environmental protection awareness have increased, various drawbacks of traditional aquaculture models have gradually emerged. Most traditional farming models often need low capital investment and have low labor skill requirements, and have become unattractive for young people due to low cash payback. Moreover, the traditional models can place pressure on limited land and other resources, and are more vulnerable to natural disasters, such as typhoon and drought. The advantages of industrial recirculating aquaculture systems (RAS) have gradually emerged. Although these systems are not without challenges, it is hoped that RAS may avoid some of the problems encountered in traditional models.

With the development of new technologies, aquaculture has transformed from traditional labor-intensive farming to mechanized aquaculture and gradually to automated systems. The labor-intensive model mainly relies on human experience, with high labor cost. RAS has greatly reduced labor demands, and production is often greatly increased. However, the automated production mode requires more skilled workers, affecting cost-effectiveness (Engle, Kumar, & van Senten, 2019), and resources such as water and feed are still impacted. With decreasing labor availability for aquaculture and increasing demand for aquaculture products, there is an urgent need for a new intelligent aquaculture model. The emergence of the Internet of Things (IoT), big data, artificial intelligence, 5G networks, cloud computing, and robot technologies makes intelligent aquaculture possible.

Intelligent aquaculture is an intelligent production mode. It employs the IoT, big data, artificial intelligence, 5G, cloud computing, robotics, through remote control or robot independent control of aquaculture facilities, equipment, and machinery to complete all production and management operations. It is the integration of modern information technology and the whole industrial chain of aquaculture production, operation, management, and service. It is a new business form of modern aquaculture development. IoT is the foundation of intelligent aquaculture, while big data acquisition and the research of big data will promote research of artificial intelligence technology used in aquaculture. In addition, big data and artificial intelligence are the core of the intelligent operation of IoT, which is essential to achieve accuracy of aquaculture control. Intelligent equipment driven by the IoT is the base of intelligent aquaculture, which could solve labor force limitations and mitigate environmental and resource problems caused by aquaculture.

Intelligent aquaculture involves the following aspects:

- Collecting information through various temperature and humidity sensors, CO₂ sensors, light sensors, dissolved oxygen sensors, various other sensors for water quality parameters, cameras, and other digital image data acquisition equipment.
- Transmitting the collected data to the control center through communication nodes. This information may include the growth of fish, environmental parameters, operation, and resource allocation.
- Data processing and decision-making performed in the cloud platform.
- Feedback of decisions to each execution equipment, and the intelligent and automatic carrying out of operations, to realize sustainable "high efficiency, high quality, ecology, health and intelligence" aquaculture.

Through advanced equipment and robotics, intelligent aquaculture can complete breeding and grow-out stages of farmed species, treatment of circulating water, precise feeding, water quality monitoring, net washing, counting, fishing, classification, and grading of animals. For example, based on water quality, fish behavior, and meteorological information, the intelligent aerator system can precisely control the aerator, the circulating water treatment equipment, and the cleaning equipment to realize the precise control of water quality. Based on biomass, water quality, environment, and behavior of the fish, combination of the intelligent feeder and deep learning can feed the fish in an appropriate and timely way to ensure healthy and fast growth of the fish. The automatic fish divider can pool and harvest fry of different sizes and ages. The fault diagnosis and early warning system is designed to guarantee safe operation of the circulating water system at all times.

2 | IMPORTANT ASPECTS OF INTELLIGENT AQUACULTURE

2.1 | Sensor technology

Sensors play an essential role in the development of intelligent aquaculture (Su, Sutarlie, & Loh, 2020). At present, the sensor industry is developing rapidly. Breakthroughs in core sensor technology, development of modern information technology, rapid development of cloud technology, construction of big data platforms, and enhancement of application and promotion, all mean that the application of sensors will be more extensive in breeding, adult fish grow-out, aquatic product storage and transportation, aquatic product processing, operation, and maintenance of intelligent fishery equipment. At the same time, increasing demands on sensor technology are driving development of novel sensors with high accuracy, high performance, multi-function, low cost, miniaturization, networking capacity, and longer service life. This has opened up prospects for the integration of sensors with the further development of new technologies in modern physics such as nanotechnology, laser, infrared, ultrasound, microwave, optical fiber, strong magnet, radioactive isotope, and the continuous development of integration technology (Sharma, Pant, & Mathur, 2019). Other important trends in development of sensors include integrating the micrometer-level sensitive sensing elements, signal detection, conversion processing circuits, and the CPU of the computer on single silicon chips, so as to develop multifunctional small portable sensors with a wider application range, high reliability, and long service life. Biosensing is another future direction of sensing technology (Moretto & Kalcher, 2014). It is believed that with the development and application of new sensors in all aspects of intelligent aquaculture, field monitoring, remote debugging, remote fault diagnosis, remote data collection, and real-time operation can be realized through IoT, enabling unmanned intelligent aquaculture production (Jennifer, 2017).

2.2 | IoT technology

Unmanned, intelligent, and high-precision farming is progressing fast in agriculture, but there are still many obstacles to deploy it fully in aquaculture. Due to the high-risk nature of aquaculture practices, a total lack of human management is difficult to imagine in the foreseeable future. Nevertheless, a large amount of intelligent equipment, including micro- and nanosensors responsible for monitoring fishery environment information, bionic robots for operation production and automatic inspection, intelligent sorting, and energy-saving processing equipment for aquatic products would greatly automate different stages of aquaculture and save labor. Every item of equipment will be interconnected through the IoT, "cloud-network-edge-end." Whether the unmanned operating ground can perform under the optimal production conditions directly depends on the real-time, security, reliability, and accuracy of the "collaborative cooperation" among the equipment (Martin, 2019). In the future, the "network" layer of IoT of aquaculture must meet the following requirements for information transmission technology. First, seamless network coverage, that is, all network equipment in the unmanned farm has access to the network, which is not limited by geographical

location or time. Second, the peak transmission rate can reach 100 Mbps~1 Gbps (5G technology), positioning accuracy to centimeter level, and network delay reduced to microsecond level. Third, the probability of network interruption is less than one-millionth with ultrahigh reliability and the high density of 100 equipment connections per cubic meter. Fourth, support of multi-network integration, business integration, and seamless connection of ground, satellite, and airborne networks. Fifth, deep integration with new technologies such as artificial intelligence will improve the intelligence level of fishery equipment in perception, positioning, and resource allocation (Jenssen, 2019). Sixth, in terms of network transmission security, the future aquaculture information transmission technology should have the ability to resist network attacks and trace the source of attacks.

2.3 | Intelligent information processing model

An important issue in aquaculture is monitoring and predicting individual information of cultured fish. This need can be met using intelligent information processing models. From the latest development, it seems that fish identification (species, size, gender), mass estimation (counting, size measurement, quality assessment), and behavioral monitoring have been quite extensively dealt with and there are satisfactory general solutions. However, application of information technologies in aquaculture is more complicated, because the inspected subjects are sensitive, prone to stress and free to move, and environment in which lighting, visibility, and stability are not controllable in most cases. The equipment must operate underwater or in a wet environment and is expected to be inexpensive. These add more difficulties to the establishment of models, make the challenge far more difficult relative to other animal husbandries, so there are not yet commercial applications widely in use and the desired results have not been achieved at present.

Intelligent information processing models have made some progress, but have not yet matured into useful tools for aquaculture. There are some problems associated with intelligent models, which cannot explain the biological mechanisms responsible for the observed patterns, and extrapolated results for data outside the range of the model have large errors. However, there are many potential applications for the technology in aquaculture that could improve product quality or production efficiency. Although some countries have conducted a lot of research on the application of intelligent models on aquaculture, the experimental settings were relatively simple, the interference was small, and most were still in the experimental phase. There are still many details to study further, such as nonlinear calibration models, combining data mining and information technology, support vector machines and memory-based learning, artificial neural network, and deep learning to improve the aforementioned technologies for commercialization and adoption by industrial sectors.

2.4 | Equipment digitization, precision control, and edge computing

Intelligent aquaculture needs precise equipment control to achieve automatic operation of the aquaculture system. Take the aeration equipment as an example. In the traditional model, the farmer must manually turn on or off the switch to control the oxygen content in the water. In the modern sensor era, farmers can remotely use computer terminals or mobile phones to send commands to control the equipment, so that the actuators such as pump and aerator will be turned on and off automatically. In latest developments, the intelligent aquaculture system can directly send the oxygen measurement to the system through the sensor, and the system can understand the dissolved oxygen in the water in real time. Based on the collected data and parameter threshold, the centralized controller can automatically turn on or off water pump, electronic valve, or water treatment equipment.

Clearly, stable and reliable sensors and professional expert database are the key to maintain good performance of the equipment. The complex aquaculture environment may affect the actuator meaning the machine may have a short service life. If machine failure cannot be dealt within time, it will lead to the interruption of the automation

process, with serious consequences. Although some experts have done a lot of research on troubleshooting techniques for equipment used in aquaculture, only a small number of machines are involved and most are still in the experimental stage. Therefore, further research should be conducted to strengthen the monitoring of equipment to improve the accuracy and integrity of the intelligent aquaculture system.

2.5 | Big data and cloud platform

Accurate monitoring, detection, and optimal control of aquaculture are extremely difficult with its special object, complex environment, and many influencing factors (Rao, Reddy, & Sucharita, 2018). The fundamental way to solve these problems is to combine big data technology with the cloud platform, process and analyze a large amount of data produced by aquaculture practices, and present useful results to producers and decision makers in an intuitive form (Roy, 2020). Aquaculture big data and cloud platform technology is the specific application technology of big data technology in the field of aquaculture (Balakrishnan, Rani, & Ramya, 2019; Figueroa, Araneda, Correa, Lhorente, & Manuel Yáñez, 2018). Through acquisition, classification, processing, management, mining, and analysis of aquaculture data (Dzulqornain, Harun Al Rasyid, & Sukaridhoto, 2018), valuable information can be extracted and provided to producers and decision makers, so as to achieve accurate, intelligent, and optimal responses.

Big data and the cloud platform are mainly used in data collection, storage, data mining, and application in aquaculture (Chen, Li, Liu, & Tao, 2019; Cruver, 2015). Among them, data collection technology is used to collect data generated in aquaculture production, processing and sales, such as Internet data, sensor data of IoT, industrial management system, professional database, and data of traditional format. Data storage and computing technology is mainly used to solve the storage and processing problems of aquaculture data. Because of the multi-source heterogeneity of aquaculture big data, it is necessary to integrate the data before it can be stored in the target database or further processed and analyzed. The processing requirements for the diversity of aquaculture big data, data storage, and processing mean-targeted methods are required. Traditional data analysis modeling needs a lot of prior knowledge and tools, the natural laws are learned from the data by virtue of human cognitive ability, and then the mechanism models are constructed (Oliveira, Costa, José, & Fernando, 2015). The complex production environment of aquaculture results in diversity, heterogeneity, and uncertainty of data (Huang & Wu, 2016). The process of discovering the hidden knowledge and rules by human observation takes a long time, and the model established in advance may not fit the real situation well. On the other hand, under data-driven modeling processes, data analysis and mining technology can automatically discover patterns hidden in data (Ma & Ding, 2018), build aquaculture data analysis and models, integrate them on the aquaculture big data cloud platform, and provide analysis results and data services to users for decision-making.

In recent years, the combination of big data analysis technology and cloud platform technology has been used in aquaculture industry before, during, and after production (Roy, 2020). It has been used to provide solutions of aquaculture environment prediction and early warning (Diamanti, Domenikiotis, Neofitou, & Panagiota, 2019; Qu, Sun, & Pu, 2017), disease diagnosis and early warning (Govindaraju, Itroutwar, Veeramani, & Kumar, 2019), abnormal behavior detection and analysis (Lu, Yu, & Liu, 2018), market analysis and mining (Purcell, Williamson, & Nguluwe, 2018), and quality control and traceability (Freitas, Vaz-Pires, & Cmara, 2019). However, the following challenges remain:

1. Lack of or minimal sharing of aquaculture big data. The development of data collection technology and industrial scale limits the availability of aquaculture big data. The biodiversity of aquatic animals and the complexity of their growing environment pose a challenge to data acquisition. At present, a lot of research is carried out in the laboratory environment. Video image acquisition under natural (often turbid) environment conditions, such as the process of fish disease and abnormal behavior of fish, is the bottleneck of aquaculture big data.

2. Lack of intelligent analysis models and technology for aquaculture. The development of Internet and IoT technology has greatly enriched the sources of aquaculture big data, and the foundation of aquaculture big data has been formed. However, the intelligence level of aquaculture big data research still needs to be further improved.
3. Lack of correlation analysis of aquaculture data in the whole industry chain. On the one hand, the lack of spatio-temporal relevance of data itself, coupled with the differences in data scale and data quality caused by the different application depths of big data technology in aquaculture, makes incorporating the data chain impossible, along with its use in correlation analysis of various problems. On the other hand, aquaculture data before, during, and after production are separated from each other, which makes it impossible to penetrate the industrial chain, and it is also difficult to explore the implied connections, such as the quality traceability of aquatic products that cannot be integrated for the whole industrial chain.

2.6 | System integration

System integration technology is the key technology of building intelligent aquaculture. It involves connecting all kinds of aquaculture equipment and subsystems to form a whole, intelligent aquaculture. An intelligent aquaculture system is intended to form a complete, integrated solution to solve the needs of farmers, making the overall performance of the system optimal, technically advanced, feasible to implement, and flexible to use. Intelligent aquaculture system integration includes equipment system integration and application system integration.

Equipment system integration refers to the combination of different types and quantities of aquaculture equipment, such as oxygen enrichment equipment, sensors, feeding equipment, and water treatment equipment, which requires similar communication interfaces, transmission mode, working voltage, and other parameters of various equipment. Therefore, equipment system integration requires establishment of a unified standard for the parameter design of aquatic equipment, selection of equipment according to this standard, and connecting all kinds of equipment to the IoT platform for monitoring and control. In addition, the layout of the equipment should be optimized to maximize their efficiency.

Application system integration refers to the integration of each subsystem and expert knowledge base in the intelligent aquaculture ground, such as water quality monitoring system, data intelligent processing system, and fish pest knowledge base. The integration of each subsystem is mainly to solve the data call, data communication, and other problems between each system. Cloud computing, edge computing, and other approaches can provide a good solution to integration of application system.

In summary, the integration of intelligent aquaculture systems is based on the needs of users, the design of intelligent aquatic equipment and technologies, and the use of other auxiliary technologies to solve various problems in system construction. Higher system stability, data processing speed, and production intelligence are the main research directions of intelligent aquaculture system integration. At present, 5G technology and cloud computing are of great significance to intelligent aquaculture systems, but reliable intelligent algorithms and long-term stable operation equipment are still understudied in intelligent aquaculture systems.

3 | FUTURE PROSPECTS

Intelligent aquaculture can improve sustainability and efficiency of resource utilization in various aspects. It can also reduce labor cost, improve productivity, and increase the quality of aquatic products. However, other factors, such as high capital cost and energy cost should be addressed to improve intelligent aquaculture. The following is an incomplete list of future prospects and challenges:

1. Intelligent aquaculture has the potential to reduce waste discharge, recycle waste, and improve resource utilization. That is, it can reduce feed use and provide better control of waste and water quality through big-data analyses and instant adjustments. To realize green and sustainable ecological aquaculture, more work needs to be done, such as saving energy by applying renewable energy facilities and saving water use through better (e.g., aquaponics) systems.
2. Intelligent aquaculture can greatly improve the output, quality, and safety level of aquatic products and can comprehensively reduce the production and operation costs of aquatic products. For example, intelligent real-time monitoring and management can monitor the health of the environment and fish. It can keep the fish in the best growth condition and improve the quality of the fish. However, there are trade-offs in reducing labor costs, such as increasing capital and energy costs; thus, more research and economic analysis will be needed throughout to identify ways for intelligent aquaculture to be economically viable. In addition, due to the high-risk nature of aquaculture, a failure of sensor or other components can lead to catastrophic error and crop loss, so models that are more robust need to be developed to achieve a fully unmanned operation system.
3. Intelligent climate and aquaculture environmental information management can help to increase aquaculture volumes and reduce losses. This is conducive to solving the problem of demand for seafood, so as to protect wild resources.
4. The application of intelligent equipment and robotics can free up labor and improve production efficiency. In addition, intelligent aquaculture can promote economic development by promoting intelligent industry and the transformation of the workforce with demand for technical talents.

Although aquaculture involves more and more technologies, it is still far from the level of other agro-food industries. The advances in technologies such as Big Data, robotics, IoT, and simulation are increasingly applied during the production process.

The core technology of intelligent aquaculture is the artificial intelligence technology platform, which integrates digitalization, industrialization, mechanization, big data information and so on. Many decisions of “intelligent aquaculture” are still based on experience rather than real data so far. Therefore, sustainable development of intelligent aquaculture model is necessary to integrate traditional aquaculture with intelligent technology, breeding technology, and information technology to realize automatic aquaculture production and information management.

Furthermore, policy and organization are also important factors that affect the sustainable development of the intelligent aquaculture model. Policy and organization will be restraining factors on innovation research and development of intelligent aquaculture if the reform of the scientific research system and innovation mechanism lags behind the need of the market created for this aquaculture model.

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