DEVELOPMENT AND EVALUATION OF AN IoT-BASED PORTABLE WATER QUALITY MONITORING SYSTEM FOR AQUACULTURE
/
基于 IoT 的便携式养殖水质监测系统的开发与评估

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ABSTRACT
In this paper, the development of a portable, multifunctional water quality monitoring system for aquaculture that is based on IoT technology is presented. The system integrates a main control module, sensor module, Human Machine Interface (HMI) module, Wi-Fi module and power module, and is equipped with system software based on Real Time Operating System (RTOS) for scheduling tasks. The main control module collects crucial water quality information, including water temperature (WT), dissolved oxygen (DO), ammonia nitrogen (NH3-N), and pH, through the sensor module and facilitates data interaction with the HMI module. The proposed aquaculture water quality evaluation model utilizes water quality parameters as input to assign a grade based on the evaluation result. These parameters are transmitted wirelessly to the OneNet cloud platform using Wi-Fi modules, enabling users to remotely monitor the water quality through a visual interface. The system structure has been meticulously designed to accommodate both portable and fixed-point remote monitoring applications. The experimental results demonstrate that the system is accurate, stable, and cost-effective, providing a reliable and efficient solution for intelligent aquaculture in small and medium-sized enterprises.

摘要
在本文中，我们介绍了一种基于物联网技术的便携式多功能水产养殖水质监测系统的开发。该系统集成了主控模块、传感器模块、人机交互模块（HMI）、Wi-Fi 模块和电源模块，并配备了基于实时操作系统（RTOS）的系统软件来调度任务。主控制模块通过传感器模块收集关键的水质信息，包括水温（WT）、溶解氧（DO）、氨氮（NH3-N）和 pH 等，并负责与 HMI 模块进行数据交互。提出的水产养殖水质评价模型利用水质参数作为输入，根据评价结果进行水质分级。这些水质参数通过 Wi-Fi 模块远程传输到 OneNet 云平台，使用户可以通过可视化界面远程实时监测水质情况。该系统结构经过特定设计，可以支持便携式使用和定点远程监测使用，实现多功能。实验结果表明，该系统准确率高、稳定性好、成本低，为中小型水产养殖企业的智能水产养殖发展提供了可靠、高效的解决方案。

INTRODUCTION
As the Agriculture 4.0 era continues to evolve, the application of IoT technologies in aquaculture is becoming increasingly prevalent *(Prapti et al., 2022)*. The quality of rearing water is critical for the growth, development, and survival of aquaculture species, while poor water quality increases the incidence of disease among species, leading to significant economic losses and environmental pollution *(Giacomazzo et al., 2020; Hongpin et al., 2015).* Hence, monitoring water quality for aquaculture is of utmost importance.

Recent years have seen continuous research into environmental monitoring systems using IoT technology *(Zhenfeng et al., 2023; Irfan et al., 2022),* resulting in significant advancements in water quality monitoring, as summarized in Table 1.

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The low power consumption, long transmission distance, and easy networking capabilities of NB-IoT and LoRa communication technologies make them ideal for large-scale, multi-node water quality monitoring applications. *Jamroen et al. (2023)* proposed a water quality monitoring system based on NB-IoT, which is powered by both photovoltaic energy and battery energy storage (BES). *Huiying et al. (2021)* proposed a multi-node aquaculture environment monitoring system based on LoRa technology. Despite their relatively short communication distance, technologies such as Wi-Fi and Bluetooth are frequently used in water quality remote monitoring studies due to their cost-effectiveness, high stability, and ease of installation. *Lin et al. (2021)* developed a wireless multi-sensor system using an ESP32 Wi-Fi module to monitor temperature, pH, DO, and EC in freshwater aquaculture. *Kelechi et al. (2021)* designed a Bluetooth-based IoT water quality monitoring system that transmitted data to a mobile application for analysis. Water quality monitoring systems are increasingly incorporating various evaluation methods in addition to remote monitoring of water quality parameters, providing a more comprehensive assessment of water quality. *Le Phuong Truong (2021)* developed a water quality monitoring, evaluation, and warning system for fish farming that includes a mobile phone short message service and web-based alert function. *Sung et al. (2021)* developed an IoT-based water quality monitoring system for water sources, proposing a flowing water quality model based on diversion-method-related experiments.

Table 1

Different studies on water quality monitoring system

Reference number	Main control platform	Measurement parameters	Network technology	Remote monitoring platform
[10]	Arduino Mega 2560	DO, pH, EC	NB-IoT	Grafana
[7]	stm32f103c8t6	T, DO, pH	LoRa	Software platform
[13]	ESP32 Wi-Fi	T, pH, DO, EC	Wi-Fi	ThingSpeak
[11]	ATmega328p	T, pH, turbidity	Bluetooth	Mobile app
[14]	Arduino Mega 2560	T, pH, DO	Wi-Fi and GSM	ThingSpeak
[19]	Arduino UNO board	T, pH, turbidity, conductivity, TDS	Wi-Fi	ThingSpeak

Numerous studies have demonstrated the efficiency, cost-effectiveness, and ease of deployment of IoT-based water quality monitoring systems. DO is one of the water quality parameters most directly related to water pollution, as well as to aquatic biota *(Csábrági et al., 2019)*. High concentrations of NH3-N can significantly impact the quality of water, and pH and WT are also critical indicators in water quality monitoring *(Santos et al., 2022; Jiaqi et al., 2019)*. In this study, the monitoring efforts were focused on four key water quality parameters: DO, NH3-N, WT, and pH. High-yield, large-scale aquaculture facilities typically use WSN technology to monitor water quality, using a set of sensors at each monitoring point to measure data and transmit it to a central monitoring center for real-time online monitoring. However, the cost of these sensors makes it unaffordable for medium and small-scale aquaculture operations to equip each breeding pool node with its own set of sensors *(Aldo et al., 2022)*.

After considering the above factors, a portable and multifunctional water quality monitoring system for aquaculture, which is based on IoT technology, was developed. To enable functional customization, our own system control circuit was designed instead of utilizing commercial development boards like Arduino. Compared with traditional water quality monitoring systems, this system is structurally designed to be portable, making it easy to transport and use. Additionally, a number of sensor interfaces are reserved for functional expansion according to requirements and IoT technology was incorporated to enable fixed-point remote real-time monitoring, allowing for long-term online monitoring of potential problematic aquaculture areas. To improve the overall assessment of water quality, an aquaculture water quality evaluation model was developed based on relevant standards. This model allows for a more comprehensive and accurate evaluation of water quality in aquaculture settings.

MATERIALS AND METHODS

System architecture

The complete system architecture is illustrated in Fig. 1, which consists of three main components: the perception layer, the network layer, and the application layer. The perception layer comprises the microprocessor and various water quality sensors. It executes multiple tasks using RTOS to collect water quality information, evaluate water quality, and transmit resulting data. The network layer connects remotely to the OneNet cloud platform via Wi-Fi. It uses the Message Queuing Telemetry Transport (MQTT) protocol to upload water quality parameters acquired by the sensing layer to the cloud platform. The client-oriented application layer enables users to interact with the system and view water quality information through the HMI. It also provides visual monitoring interfaces on PC and mobile terminals, allowing users to remotely monitor water quality information via mobile app and PC.

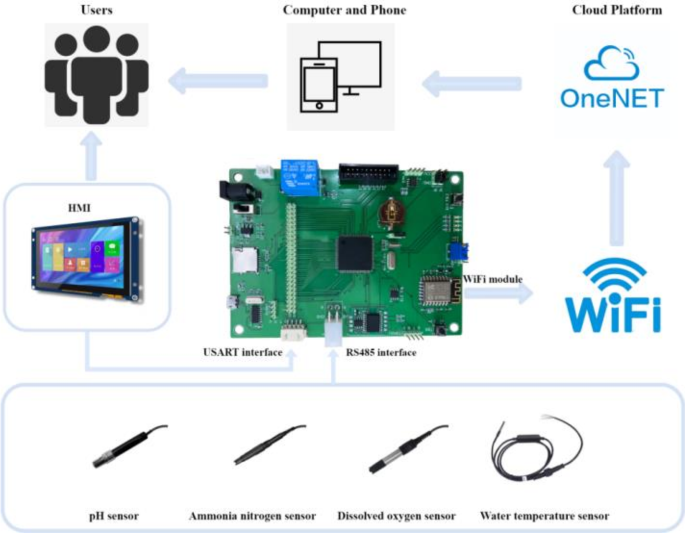


Fig. 1 - System architecture

Sensors for water monitoring

High-precision water quality monitoring sensors from SINO IoT Company (China) were chosen to measure DO, NH3-N, and pH, and a temperature sensor manufactured by DALLAS Semiconductor Company (USA) to measure WT. Table 2 displays the sensors' parameters that support the Modbus transmission protocol and meet the system requirements with high accuracy. Implementing and maintaining Modbus is simpler than other standards and allows multiple devices to connect to the same cable, facilitating communication and enhancing convenience in design *(Miao et al., 2022)*. Modbus also enables the addition of more sensor types in the future while imposing minimal constraints.

Table 2

Parameters of water quality sensors

Sensor types	Measurement range	Accuracy	Resolution	Transmission protocol	Power supply mode
Temperature sensor	-55~80℃	±0.5℃	0.1℃	Modbus	DC 5V
Dissolved oxygen sensor	0~20mg/L	±5%	0.01 mg/L	Modbus	DC 5V
pH sensor	0~14PH	±3%	0.01PH	Modbus	DC 5V-9V
Ammonia nitrogen sensor	0~18g/L	±5%	0.01 mg/L	Modbus	DC 5V-12V

Hardware design

Figure 2 illustrates the hardware architecture of the system, which comprises a single-chip microcontroller module, a RS485 module, an ESP8266 module, and a power module. The GD32F303 series main control produced by GigaDevice Semiconductor Inc. is adopted as microsystem controller (it is a 32-bit general microcontroller based on Arm Cortex-M4 core, with abundant peripheral resources and low cost). The RS485 module transmits the data collected from the sensors to the system master control.

The ESP8266 module enables a connection to a Wi-Fi network, allowing for the remote transmission of data. The power module supplies two power sources of 5V and 3.3V to the system to power the various modules. A design for the connection interface of the HMI module and the debugging download interface, which facilitates the connection and program debugging of the HMI module, was proposed. In addition, some functions and input/output (IO) ports are reserved, such as SD card module, relay module and some of the main controller IO ports, to facilitate the subsequent system function upgrade. The peripheral circuit design of each functional module is implemented and integrated into a single Printed Circuit Board (PCB).

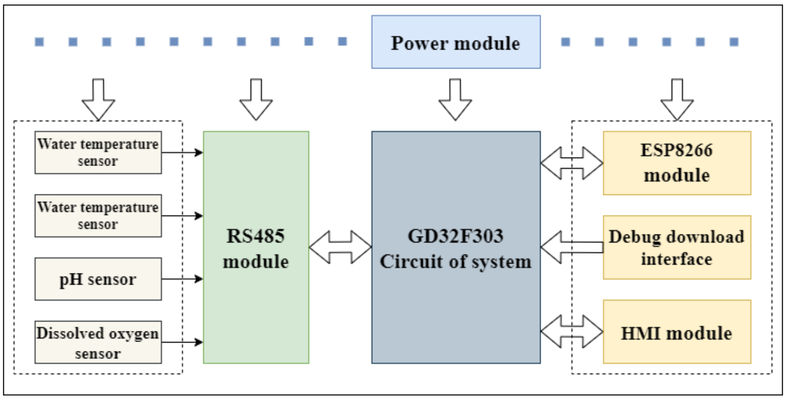
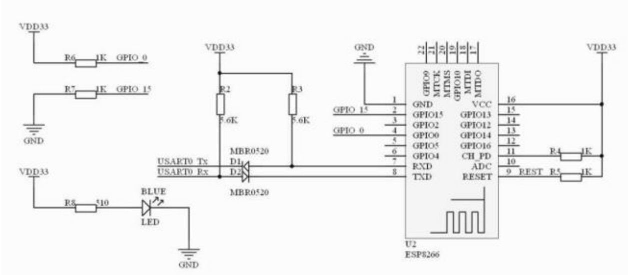
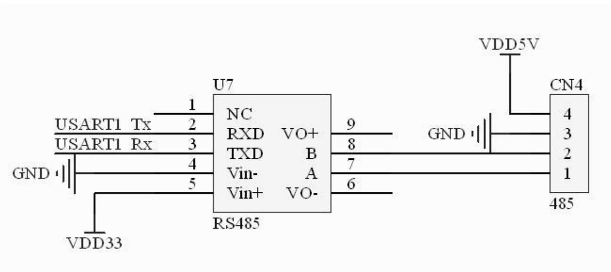


Fig. 2 - Design block diagram of main control board

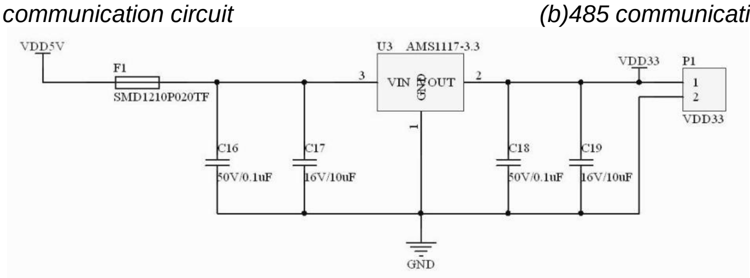
The main functional circuits of the system hardware include Wi-Fi communication circuit, 485 communication circuit and power supply circuit. Figure 3a shows the Wi-Fi communication circuit, the controller transmits AT commands through serial port 0 to the ESP8266 module to establish a Wi-Fi connection. Figure 3b illustrates the 485-communication circuit. The RS485 to UART_TTL module is used to communicate between the master controller via Serial Port 1 and the external sensors to obtain digital signals. The main controller board requires an external input voltage of 5V, as well as a 3.3V voltage to power the necessary modules. The voltage conversion circuit based on AMS1117 chip is shown in Fig. 3c. Adding decoupling capacitors at the input and output can enhance the transient current response time, minimize output voltage noise and ripple, and promote a stable 3.3V output.



(a)Wi-Fi communication circuit



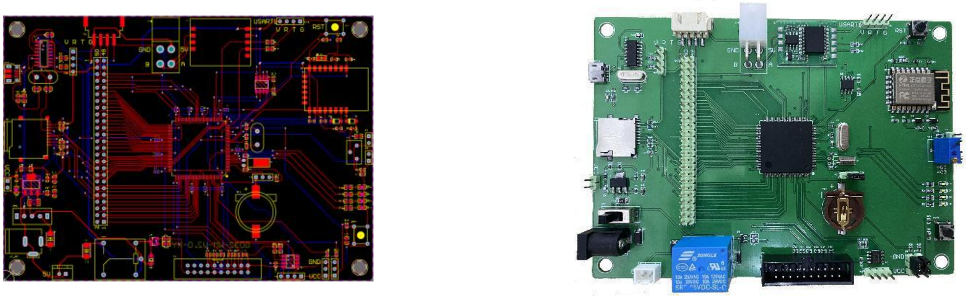
(b)485 communication circuit



(c)voltage conversion circuit

Fig. 3 - Schematic diagram of main functional circuits

The PCB design of the main control board was completed using Altium Designer (AD) software, and all components were reasonably laid out according to the functional modules, in order to facilitate wiring and ensure the stability of the circuit board, a double-sided board was used in this design. According to the reasonable electrical rules, the PCB Layout diagram is shown in Fig. 4a, and the actual circuit board is shown in Fig. 4b. SolidWorks and CAD software were utilized to design the device's structure. This design allows for both portable and fixed-point usage, as demonstrated in Fig. 5.



(a)PCB layout *(b)real product*

Fig. 4 - The electronic board

(a)for portable usage *(b)fixed point of usage*

Fig. 5 - A 3D view of the structure of equipment

Software development

The system software process is shown in Fig. 6, which is developed based on the lightweight system OpenHarmony. OpenHarmony uses a preemptive scheduling mechanism and includes 32 priority task modules. High-priority tasks can preempt low-priority tasks, while low-priority tasks can only be scheduled after high-priority tasks have been blocked or completed *(OpenAtom)*.

Upon system startup, hardware initialization is performed, which primarily involves setting the parameters for GPIO, serial port, timer, and other modules. After, the system kernel is launched, and three threads with varying priorities are created, from high to low, respectively: (1) the sensor data acquisition thread: This thread acquires water quality parameter information from temperature, DO, pH, and NH3-N sensors, based on the sampling frequency set by the timer. (2) water quality assessment thread: This thread processes the sensor values obtained by the data acquisition thread, using them as inputs to the water quality assessment model and calculates the pollution index and water quality grade. (3) the Wi-Fi communication thread: Establishes a connection to a designated Wi-Fi network through HMI, ensures accurate data transmission using CRC verification algorithm, accesses OneNet cloud platform, and remotely transmits data using MQTT protocol at a specified frequency.

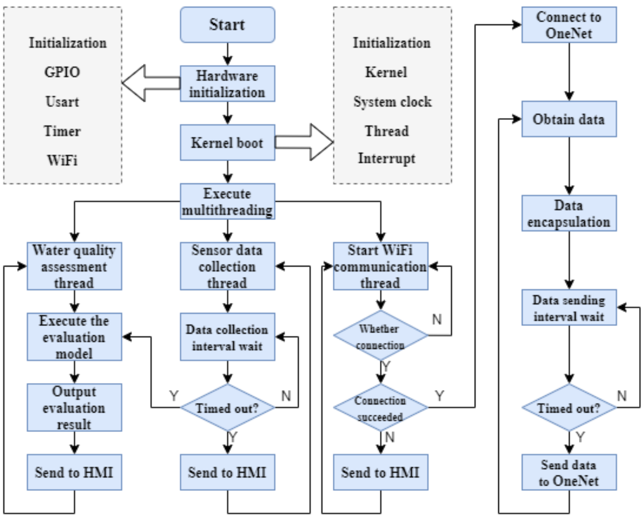


Fig. 6 - System software flowchart

As a leading country in aquaculture, China has maintained its position as the world's top producer of aquaculture for several years *(Kangshun et al., 2021)*. China has developed a range of aquaculture standards based on extensive breeding experience and input from numerous experts. Our team established an aquaculture water quality evaluation model for obtaining the comprehensive pollution index and water quality grade by calculating the single-item pollution index according to the *Specification for Monitoring Environmental Quality of Farm Water Sources (NY/T 396-2000)*.

The single-item pollution index of water quality is calculated according to Eq. (1). To calculate the single-item pollution index for indicators such as DO, which decrease in concentration with increasing pollution, Eq. (2) was used. For the indicator with limited range (the allowable range of pH is 6~9), the single-item pollution index is calculated according to Eqs. (3) and (4). The comprehensive pollution index of water quality is calculated using Eq. (5).

$$W_i = \frac{P_m}{P_s} \tag{1}$$

$$W_i = \frac{P_t - P_m}{P_t - P_s} \tag{2}$$

$$W_i = \frac{P_m - A_{avg}}{A_{min/max} - A_{avg}} \tag{3}$$

$$A_{avg} = \frac{A_{min} + A_{max}}{2} \tag{4}$$

$$W_c = \sqrt{\frac{(W_{avg})^2 + (W_{max})^2}{2}} \tag{5}$$

where:

W_i refers to single-item pollution index of water quality, P_m is a measured value of water pollutant, P_s refers to pollutant quality standard, P_t refers to the theoretical maximum value of a pollutant, A_{avg} is an average value of allowable range, $A_{min/max}$ refers to the maximum or minimum of allowable range, W_c refers to composite pollution index, W_{avg} is a value of average single-item pollution index, W_{max} is a value of Maximum single-item pollution index.

If the single-item pollution index is less than 1, its value is equal to the calculated value. However, if the single-item pollution index is greater than or equal to 1, it is recalculated using Eq. (6).

$$W_i = M + P * lg\,(W_i) \tag{6}$$

where P is a constant 5, M is a constant 1.

In the above formula, the standard limit values of each item (P_s, P_t, $A_{min/max}$) are determined according to *the Basic Standard Limit Values of Environment Quality of Surface Water (GB 3838-2002)* Ⅲ indicators (applicable to aquaculture and other fishing waters). According to the *Fishery Water Quality Standards (GB 11607-89)*, and *NY/T 396-2000*, the water quality is classified based on the comprehensive pollution index (CPI), as shown in Table 3, divided into three water quality levels (WQL).

Table 3

Water quality classification standard

Classification of grades	Composite pollution index	Water quality level
1	≤0.5	Good
2	0.5~1.0	Qualified
3	≥1.0	Poor

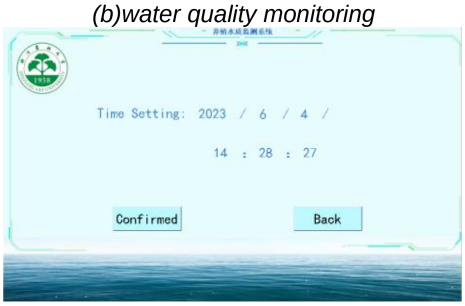
***Interface design of HMI and remote* visualization**

The HMI design is based on the system's requirements, which consists of four main interfaces: function selection, water quality monitoring, network connection, and system setting. The function selection interface allows users to choose the desired system functions. The water quality monitoring interface provides a clear and intuitive display of water quality parameters. The network connection interface enables users to connect to a Wi-Fi network. Lastly, the system settings interface allows users to calibrate the system's time setting. The HMI interface, as depicted in the in Fig. 7, was tailored to support the portable use of the system effectively.

(a)function selection

(b)water quality monitoring

(c)network connection

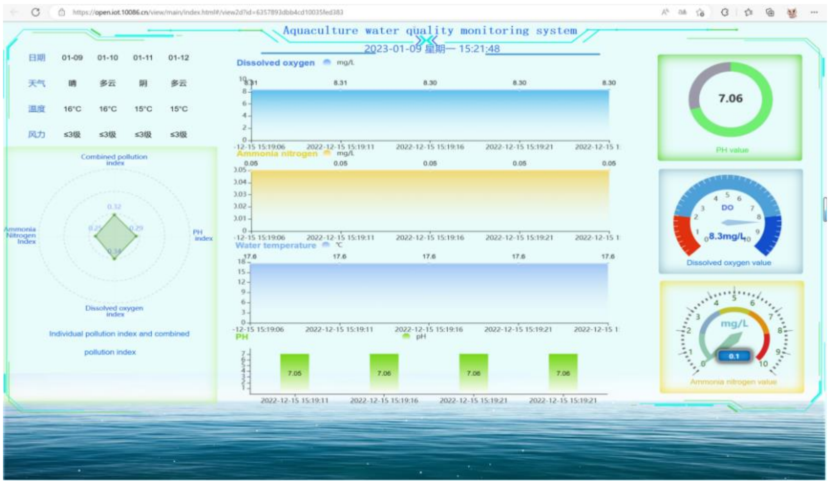


(d)system setting

Fig. 7 - Interface design of HMI

A remote visualization interface for water quality parameters was developed using the data visualization View service provided by the OneNet cloud platform. The PC-side visual interface comprises several modules, including the weather module, pollution index module, monitoring module, and parameter display module, as illustrated in Fig. 8a. This interface allows remote monitoring of the trend of each water quality parameter over time and provides latest access to key water quality information. Users can also access weather conditions for the current day and the following three days, as well as individual and composite pollution indices of the water quality.

To provide a mobile solution, a visualization interface for smartphones was also developed, as depicted in Fig. 8b. With this interface, users can view the main parameters of the breeding water quality as long as their mobile device is within network range.



(a)visualization interface on PC

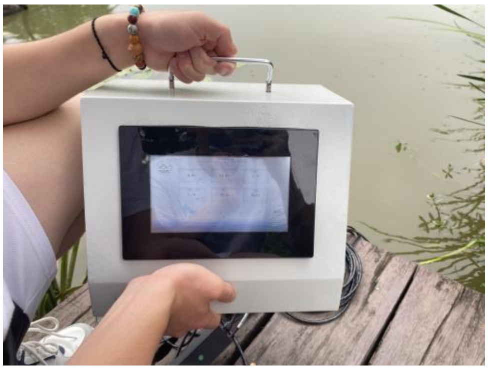
(b)mobile visualization interface

Fig. 8 - Visual interface design

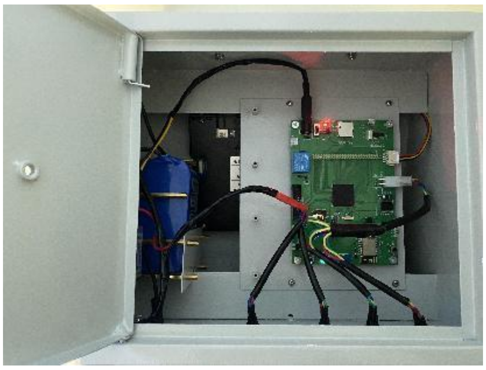
RESULTS

The sensors have been pre-calibrated by the manufacturer. A physical prototype of the equipment is displayed in Fig. 9 and the sensors are connected to the device through the aviation interface located at the bottom of the device. Figure 9a displays the front of the device, which primarily comprises the HMI interface. Figure 9b depicts the internal circuit of the device. The system is powered by a 15V lithium battery, which outputs a stabilized 5V voltage to the main control board through a voltage stabilized module.

To test the accuracy of the measurement data in the system, standard solutions with three different values for NH3-N and pH parameters were used. The corresponding sensors in the system were used to measure standard solutions, and the measurement average value (MAV) was calculated for each solution by measuring it five times. The accuracy of the data was compared by comparing the DO and WT parameters with the AR8010 device (the AR8010 is a high precision DO analyzer produced by SMART SENSOR company in China, and the DO measurement range is 0-20mg/L, with a resolution of 0.01mg/L). Three different measurement points in a water body were selected and the DO and WT values were measured using both the AR8010 device and the system. Each point was measured five times and the average value was calculated for each measurement separately. The accuracy of the measurement data was evaluated by calculating the relative error (RE) and the mean relative error (MRE). The final test results are shown in Table 4. The MRE for pH and WT parameters were respectively 0.37% and 0.7%. The MRE for NH3-N and DO parameters were 1.73% and 1.93%, respectively. These results indicate that the overall measurement error of the system was low, demonstrating its high accuracy.



(a)equipment front



(b)internal circuit

Fig. 9 - Physical view of the system

Table 4

System accuracy analysis of measurement

Items	Reference objects	Reference values	MAV	RE/%	MRE/%
NH3-N	NH3-N standard solution	0.5mg/L	0.51mg/L	2	1.73
		1mg/L	1.02mg/L	2	
		5mg/L	5.06mg/L	1.2	
pH	pH standard solution	4.0	4.02	0.5	0.37
		6.86	6.88	0.29	
		9.18	9.21	0.33	
DO	AR8010	5.62mg/L	5.54mg/L	1.42	1.93
		6.21mg/L	6.12mg/L	1.45	
		6.88mg/L	6.68mg/L	2.91	
WT	AR8010	22.6℃	22.5℃	0.44	0.7
		23.8℃	23.6℃	0.84	
		24.2℃	24℃	0.83	

In OneNet, a device is created for the system, and device information and number are added. After the unique authentication information assigned by OneNet is successfully bound to the system, it can store the data sent by the system, such as pH, DO, NH3-N and WT. As shown in Fig. 10, the platform can receive real-time data from the system and query historical data based on a specified time period. Additionally, all data can be synthesized into exportable files, facilitating storage, viewing, and processing of the data. A stability test of the platform's data reception capabilities was conducted. During the test, the system sent four parameters to the platform every 5 seconds, resulting in a total of 150 sets of data. The data received by the cloud platform were collected and analyzed, and the results are shown in Table 5. The NH3-N and DO parameters did not experience any data loss, while the pH and water temperature parameters had a data loss rate of 0.7% and 1.3%, respectively. The high overall data reception rate and minimal data loss indicate strong platform stability.

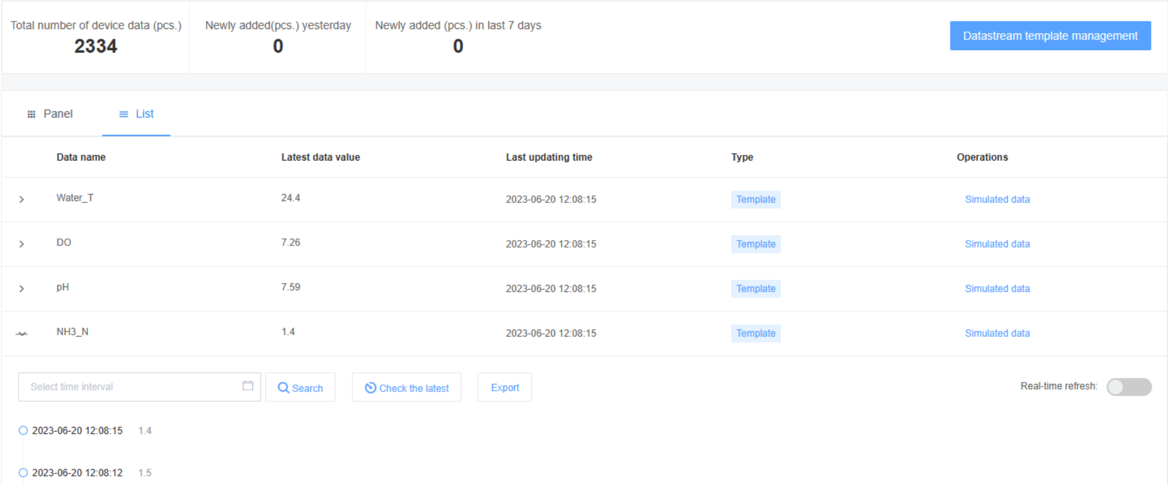


Fig. 10 - The data management interface of platform

Table 5

Cloud platform stability testing

Items	Send data volume	Received data volume	Lost data volume	Data loss rate / %
NH3-N	150	150	0	0
pH	150	149	1	0.7
DO	150	150	0	0
WT	150	148	2	1.3

CONCLUSIONS

This paper proposes a portable multi-functional aquaculture water quality monitoring system based on IoT, which integrates four sensors to measure WT, DO, NH3-N and pH. The system uploads water quality information to the OneNet cloud platform through Wi-Fi communication. The portable structure design of this system simplifies the arrangement of multiple sets of sensors, reducing hardware costs associated with water quality monitoring. This design better suits the monitoring needs of small and medium-sized aquaculture bases, while still allowing for fixed-point remote monitoring. The visualization interface designed for PC and mobile devices clearly and effectively conveys water quality information to aquaculture personnel, enabling timely detection of any issues in the water area. The establishment of a breeding water quality evaluation model enables personnel to accurately assess water quality and make necessary improvements. This system also has some shortcomings, with fewer types of water quality sensors used, but multiple 485 interfaces have been reserved, and other sensors supporting Modbus protocol can be quickly connected to the system. Experimental results demonstrate that the system provides accurate measurements, stable data transmission, and is user-friendly and easy to maintain, which can effectively address water quality monitoring needs for small and medium-sized aquaculture bases.

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