World Journal of Engineering Research
Print ISSN: 2959-9865
Online ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3107

A MULTI-MODE INTELLIGENT AQUARIUM MONITORING SYSTEM WITH IOT (INTERNET OF THINGS) REMOTE CONTROL

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Abstract: With the popularization of smart home technologies, traditional aquarium breeding suffers from issues including low monitoring accuracy, single control modes and inconvenient remote management. To address these drawbacks, this paper presents an intelligent ecological aquarium monitoring system based on STM32. Adopting the STM32F103C8T6 as the main control chip, the system integrates DS18B20, pH and TDS sensors to achieve real-time monitoring of water temperature and water quality parameters. It realizes automatic feeding, oxygenation and water circulation via servos and relays, and supports four operating modes: timing, manual, threshold and automatic, to meet diverse application requirements in different scenarios. An OLED screen enables on-site data display, while an ESP-01S Wi-Fi module uploads collected data to a mobile APP, allowing remote timing configuration, device control and threshold adjustment. Test results indicate that the system features high measurement accuracy, fast response and stable operation, and can greatly improve the management efficiency of aquarium environments. With low cost, compact size and easy deployment, this system offers an intelligent solution for household aquarium maintenance and small-scale aquaculture applications.

Keywords: STM32; Intelligent ecological aquarium; Water quality monitoring; Remote control; IOT

1 INTRODUCTION

At present, household and small-scale aquaculture still rely mainly on manual management. The traditional manual operation and maintenance mode has obvious drawbacks, including low management efficiency, delayed monitoring of environmental parameters and slow response to equipment adjustment.

According to the *China Fishery Statistical Yearbook* [1], labor costs in China's aquaculture industry account for 35% to 50% of total expenses, and the fish mortality rate caused by human operational errors exceeds 15%. In practical breeding environments, a water temperature fluctuation beyond ±2 °C can easily lead to fish stress and death. Abnormal water pH values often fail to trigger timely equipment adjustments due to delayed monitoring. Manual feeding also brings problems such as irregular feeding schedules and inaccurate feeding dosages, resulting in a feed waste rate of 20% to 30%. Auxiliary aquaculture equipment including aerators and temperature controllers is fully operated manually, with a regulation response delay of over 30 minutes. This fails to meet the real-time water environment requirements for fish growth, greatly hindering the refined and standardized development of aquarium breeding.

Nowadays, with the rapid development and iteration of the IOT and embedded technologies, intelligent transformation and upgrading of aquaculture has become the mainstream trend of the industry. Documents released by the Ministry of Industry and Information Technology explicitly state that efforts should be made to accelerate the intelligent upgrade of agricultural breeding equipment, so as to realize precise regulation of breeding environmental parameters and full-process automation of breeding operations. An intelligent breeding management and control system built based on embedded single-chip microcomputers, wireless communication and sensor detection technologies can effectively address the deficiencies of traditional manual management, and satisfy the demands for intelligent development of modern agriculture [2].

Scholars at home and abroad have conducted extensive research on intelligent fish tank and aquaculture monitoring systems. Most domestic studies adopt STM32 and ESP8266 microcontrollers as the main control units, and have gradually implemented basic functions including multi-parameter water quality collection, cloud data uploading, remote device control and precise automatic feeding. Some research has further optimized data filtering algorithms, and expanded human-machine interaction interfaces as well as energy-saving control logic. Nevertheless, most existing systems suffer from low parameter control accuracy, limited operating modes and poor coordination between local control and remote terminals [3-5].

Overseas studies mainly focus on closed-loop control algorithm optimization. They apply PID algorithms to realize high-precision constant water temperature control, and improve the logic for water quality abnormality alarms and automatic water replacement. However, such systems generally come with high hardware costs. Few lightweight designs are tailored for household small fish tanks, which restricts their large-scale application and popularization [6-8].

In summary, most existing intelligent aquarium systems suffer from limited operating modes, inadequate coordination between local and remote terminals, and a lack of lightweight designs for household use. Accordingly, this paper presents an intelligent ecological aquarium monitoring system featuring multi-mode integration, low power consumption and low cost. The main innovations of the proposed system are listed as follows:

(1) Four control modes are integrated to adapt to various breeding scenarios;

(2) Dual interaction terminals including physical local buttons and a mobile APP are adopted to improve operational flexibility;

(3) Adopting a modular design, the system features low hardware cost and simple deployment, making it suitable for widespread household application.

This system integrates real-time water quality monitoring, intelligent control and remote management, and can effectively address the deficiencies of traditional breeding methods.

2 OVERALL SYSTEM DESIGN

The system adopts a modular layered architecture for both hardware and software. The overall hardware design is illustrated in Figure 1. With the STM32F103C8T6 microcontroller as its main control core, the hardware is divided into four functional units. The perception layer employs temperature, pH and TDS sensors to collect water environment parameters, and the OLED screen enables real-time on-site data display. The execution layer uses servos to realize automatic feeding, controls water pumps and oxygen pumps via relays, and works with a buzzer to send abnormality alarms. The communication layer adopts the ESP-01S Wi-Fi module to achieve wireless data transmission between the device and the mobile APP. The interaction layer supports local parameter configuration and mode switching via physical buttons, as well as remote control through the mobile APP.

The software consists of a driver layer, a middleware layer and an application layer, which are respectively responsible for bottom peripheral driving, data processing, communication parsing and system control logic execution. The system provides four operating modes: manual, timing, threshold and automatic. It can automatically control peripheral devices and activate alarms when water environment parameters exceed preset thresholds. Meanwhile, data synchronization between the local display and mobile APP is realized, which effectively maintains stable water conditions inside the ecological aquarium.

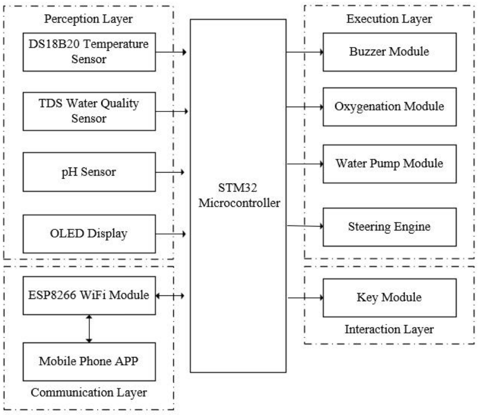


Figure 1 Overall Block Diagram of System Hardware

3 HARDWARE SYSTEM DESIGN

3.1 System Composition

The system hardware circuit adopts a modular design. Centered on the STM32F103C8T6 main control circuit, it consists of five functional modules: water environment sensor acquisition circuit, ESP-01S wireless communication circuit, servo feeding and relay load driving circuit, key and OLED display human-machine interaction circuit, and system regulated power supply circuit. All modules are independent with standardized interfaces. This design suppresses signal interference and facilitates circuit debugging and troubleshooting.

3.2 Core Hardware Circuits

3.2.1 Water parameter acquisition circuit

The DS18B20 adopts a one-wire digital interface, directly outputting temperature readings without requiring external ADC conversion, thus offering strong anti-interference capability. Compared with NTC thermistors, it requires no calibration, features excellent consistency, and is well suited for multi-node distributed temperature measurement. With a measurement range of -55 °C to +125 °C and an accuracy of ±0.5 °C, it fully satisfies the aquarium’s temperature monitoring needs within 0–40 °C.

As shown in Figure 2, the sensor interface circuit uses an external 3.3 V power supply (VDD connected to 3.3 V and GND grounded) instead of parasitic power mode to enhance long-term operation stability. The one-wire data line (DQ) is externally pulled up by a 10 kΩ resistor to ensure sharp signal edges. When configured to 12-bit resolution, the maximum conversion time is 750 ms, and the system sets the acquisition period to 1 s to meet real-time requirements.

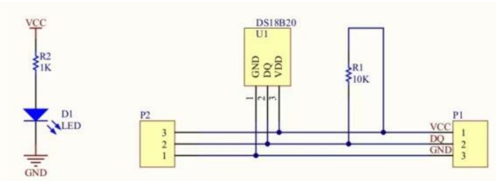


Figure 2 Interface Circuit Diagram of the DS18B20 Sensor

The pH sensor circuit employs analog signal acquisition, with the module's output analog voltage connected to the ADC pin of the microcontroller. An adaptive voltage divider and filter circuit is configured to suppress high-frequency interference from water impurities, converting the water's pH signal into a measurable electrical signal. After sampling and conversion by the main control chip, the real-time pH value can be obtained. The corresponding circuit diagram is shown in Figure 3.

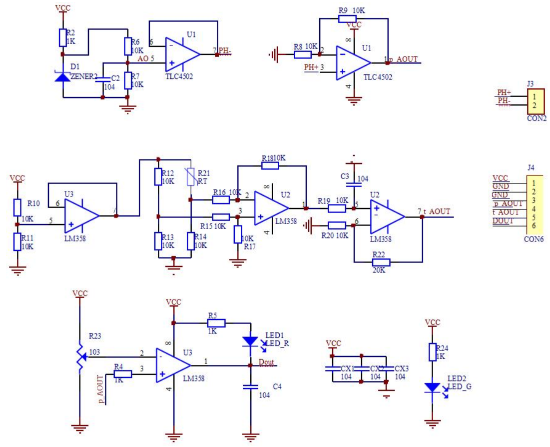


Figure 3 Internal Circuit Diagram of pH Sensor

The TDS water quality sensor outputs analog signals and connects to the microcontroller's ADC port. A filter circuit is deployed to mitigate ambient electromagnetic interference. The module converts the content of dissolved solids in water into voltage signals. The main controller samples and processes these signals to acquire the water purity value. The interface circuit is shown in Figure 4.

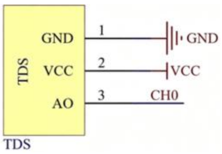


Figure 4 Interface Circuit Diagram of TDS Sensor

3.2.2 Servo drive circuits

The driving circuit for the SG90 servo utilizes the PA1 pin of the STM32 microcontroller to output PWM signals. By adjusting the duty cycle, the rotation angle of the servo is controlled to complete the automatic feeding action. Unlike stepper motors, servos require no dedicated driver chips, featuring fewer interfaces and lower costs. The corresponding drive circuit is shown in Figure 5.

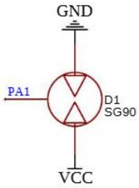


Figure 5 SG90 Servo Drive Circuit Diagram

3.2.3 WiFi communication circuit

The circuit of the ESP-01S Wi-Fi module (ESP8266 series) communicates with the STM32 main controller via UART, see Figure 6. Its VCC pin is connected to a 3.3 V regulated power supply and the GND pin is grounded for level matching. The TX and RX pins are cross-connected to the microcontroller's USART interface to achieve bidirectional data transmission.

This module integrates a TCP/IP protocol stack and supports STA and AP modes. It can be easily configured through serial AT commands. Featuring compact size and low power consumption (operating current: approximately 70 mA; sleep current: below 1 mA), it is well suited for IoT terminal applications. In addition, it costs less than the ESP32 module, at around 15 RMB per unit.

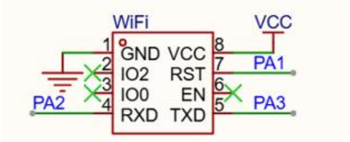


Figure 6 ESP-01S Wi-Fi Module Interface Circuit

3.2.4 Buzzer alarm circuit

The buzzer alarm circuit adopts the SS8050 NPN transistor as the switching driver. The control signal output from the STM32 pin is connected to the base of the SS8050 via a current-limiting resistor. A high-level signal turns on the transistor to energize the buzzer and activate the alarm; a low-level signal cuts off the transistor and stops the buzzer. A freewheeling diode is added to absorb the back EMF generated by the buzzer coil during power-off, protecting the transistor and main control circuit. This circuit implements audible alarm when abnormal conditions occur. The buzzer circuit is shown in Figure 7.

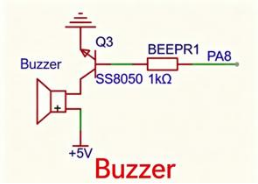


Figure 7 Buzzer Drive Circuit

4 SYSTEM SOFTWARE DESIGN

The system main program adopts a structured design consisting of power-on initialization, cyclic scheduling, and multi-mode judgment. After power-on, the STM32 first completes initialization configuration for peripherals, sensors, the Wi-Fi module, the OLED display, and other actuators, and loads preset threshold parameters. To improve data reliability, the system uses a mean filtering algorithm to process raw sensor data, suppress random noise and environmental interference, and enhance detection accuracy for water temperature, pH, and TDS. The system then enters the main loop, where it sequentially performs acquisition and processing of water temperature, pH, and TDS data, and scans key states in real time. According to the current operating mode, it executes manual, timing, threshold-based, and automatic control logic respectively. By comparing collected data with preset thresholds, the system automatically drives the servo for feeding, controls the water pump and oxygen pump through relays, and activates the buzzer alarm when parameters are abnormal. Meanwhile, the main loop processes Wi-Fi communication in real time, completes command interaction and data upload with the mobile APP, and synchronously refreshes all states and parameters on the OLED screen, realizing the integrated closed-loop operation of local monitoring, automatic control, and remote management. The main program flowchart is shown in Figure 8.

Figure 8 The Main Program Flowchart

5 IMPLEMENTATION AND TESTING

5.1 System Test Environment

To verify the system performance, separate tests are performed on each hardware module. A transparent plastic cup serves as the container, with tap water left standing for 24 hours as the test sample. An adjustable heating rod regulates the water temperature between 20 °C and 50 °C. The pH value is adjusted manually using dedicated pH adjusters (pH Down and pH Up), and milk is added to change the TDS value of the water.The overall system test is conducted in a simulated aquarium environment at an ambient temperature of 25 °C, also using 24-hour settled tap water. The test indicators include detection accuracy of water temperature, pH and TDS, device response time, Wi-Fi communication stability, working mode switching success rate, and long-term operating stability of the system.

5.2 System Core Function Test

Figure 9 presents the test procedures and key data of the temperature, pH and TDS sensors. The upper part shows the stability test of the DS18B20 temperature sensor in different water environments. When the water temperature is set to 25 °C and 50 °C, the sensor reads 25.1 °C and 49.8 °C respectively, with a detection error within ±0.3 °C, satisfying the requirements for temperature monitoring accuracy.

The middle part illustrates the two-point calibration of the pH sensor using standard buffer solutions of pH 4.00 and pH 6.86. After calibration, the sensor outputs readings of 4.02 and 6.80 for the corresponding test solutions. The error is limited to ±0.1 pH, guaranteeing reliable pH measurement for water quality.

The lower part displays the comparison test of the TDS sensor in pure water and milk solution. The measured TDS values are 244.1 mg/L and 817.6 mg/L. The sensor features fast response and excellent resolution for varying concentrations of dissolved solids. The test results indicate that all sensors meet the designed accuracy specifications, providing solid data support for stable system operation.

Figure 9 Temperature, pH and TDS Sensor Performance Test Process

Figure 10 shows the functional test process of the system actuators. In manual control mode, keys are used to drive the servo to rotate sequentially from 0 ° to 90 ° and then to 180 °, so as to verify its angle control accuracy and response consistency. The test results prove that the servo operates stably with precise positioning, fulfilling the requirements for quantitative feeding control. In automatic control mode, the system implements closed-loop control of water quality parameters based on preset thresholds. When the water temperature drops below the threshold, the buzzer activates an audible and visual alarm immediately. If the pH value is abnormal or the TDS concentration exceeds the specified range, the relay will start the water pump automatically to carry out circulating water filtration. The test results demonstrate that the servo and water pump feature fast response and reliable operation. The system runs with correct control logic and can perform corresponding actions as preset.

Figure 10 Performance Test of Servo and Water Pump Actuator

Figure 11 presents the configuration interface and test verification flow of the system's timing control mode. During the test, two timing tasks were set via the OLED display interface: the feeding actuator is activated at 08:00 and works for 30 s; the oxygen pump turns on at 12:00 with a 10- min runtime. When operating under timing control, the system can precisely trigger corresponding equipment actions at preset moments and shut down automatically upon completion of the set duration. No missed operations, false triggers or action delays occur throughout testing. Test results verify that the system features accurate and reliable timing control logic. It supports periodic automatic start-stop of peripheral devices, lowers manual operation frequency substantially and satisfies the automatic management requirements for intelligent aquarium breeding.

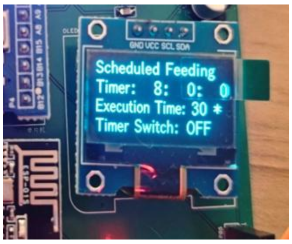
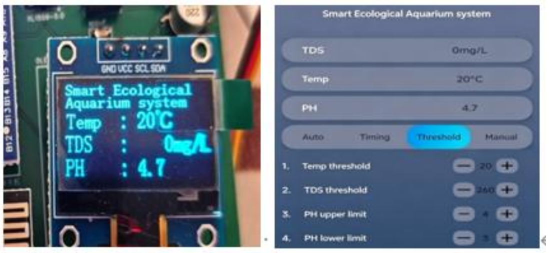

Scheduled Feeding
Timer: 8: 0: 0
Execution Time: 30 *
Timer Switch: OFF

Figure 11 Timing Control Mode Function Test

Figure 12 illustrates the data interaction between the on-board OLED display and the Android APP of the system. The left part shows the local OLED screen, which displays core water quality indicators including water temperature, TDS and pH in real time. The right side presents the APP threshold configuration page, supporting remote data checking, working mode switching, control threshold modification and timing task setup. Test results indicate that the ESP-01S WiFi module can rapidly connect to the home LAN and upload water quality data to the APP stably. Remote commands for mode switching, threshold modification and timing configuration are executed within 1 second. The system achieves favorable real-time synchronization of data and commands, satisfying the requirements for remote monitoring and management of the aquarium control system.


Smart Ecological Aquarium system
Temp : 20℃
TDS : 0mg/L
PH : 4.7

Smart Ecological Aquarium system
TDS 0mg/L
Temp 20°C
PH 4.7
Auto Timing Threshold Manual
1. Temp threshold 20
2. TDS threshold 260
3. PH upper limit 4
4. PH lower limit 5

Figure 12 Remote Interaction Interface Between Local Display and Mobile APP

5.3 Performance Index and Error Analysis

To fully verify the detection accuracy, response speed and operational stability of the system, key performance indicators were tested and corresponding error analysis was performed. The main system performance parameters are listed as Table 1.

Table 1 Main System Performance Parameters

Detection parameters	Measurement error	Response time
Temperature	≤±0.5℃	<1s
PH value	≤±0.1	<1s
TDS value	≤±10 mg/L	<1s
commanded response	—	<1s
72 hours operation	No abnormal	Stability

As shown in Table 1, the measurement errors of water temperature, pH and TDS are within the designed allowable range of the system. The sensor response time is shorter than 1 s, enabling real-time tracking of water quality variations. The response latency for remote commands is also below 1 s, satisfying the requirement for real-time interaction. During the 72-hour continuous running test, the system experienced no missing collected data, unexpected equipment shutdowns or control logic faults, demonstrating favourable stability and reliability. Repeated experiments verify that the system's detection precision, real-time capability and stability conform to design specifications, supporting long-term stable monitoring and automatic control of aquarium environments.

6 CONCLUSION

The intelligent ecological aquarium monitoring system proposed in this paper integrates multi-sensor measurement, multimode control and WiFi remote communication to realize automatic and intelligent management of aquarium environments. Featuring compact structure, low cost, stable operation and easy expandability, the system effectively reduces manual dependence and improves the safety of aquatic breeding. In follow-up research, combining an IoT cloud platform with machine learning algorithms enables water quality prediction and intelligent decision-making, further upgrading the overall intelligence of the system.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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