Intelligent Aquaculture Monitoring and Automatic Feeding Cruise System Based on STM32

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Abstract: *Targeting the pain points of traditional aquaculture—low manual management efficiency, delayed water quality control, and high labor costs—this paper presents an STM32-based intelligent aquaculture monitoring and automatic feeding cruise system. With STM32F103 as the core, the system integrates water quality sensors (temperature, pH, dissolved oxygen, turbidity), Bluetooth module, motor drivers, and a steering gear feeding unit. It implements optimal-path cruise via PID algorithm and remote monitoring/control via Bluetooth. Tests verify stable water quality data collection, timed quantitative feeding, and preset-path autonomous cruising. The system effectively reduces manual monitoring costs, offering a low-cost, practical intelligent solution for small-to-medium aquaculture farms.*

Key words: *STM32; aquaculture; water quality monitoring; intelligent feeding; PID control*

Introduction

As a vital component of modern agriculture, the aquaculture industry has witnessed continuous growth in both scale and output, and has become a key pillar industry for promoting rural industrial restructuring and increasing farmers' income[1]. Currently, most aquaculture operators in China still rely on traditional management modes based on manual inspections and empirical judgments, which commonly suffer from high labor costs, untimely water quality monitoring, low feeding precision, and lagging environmental regulation, making it difficult to meet the requirements of intensive and green aquaculture development[2-3]. With the rapid development of the Internet of Things, embedded systems, and intelligent control technologies, it has become an industry consensus that aquaculture equipment should be upgraded toward intelligent, automated, and mobile directions[4].

In recent years, scholars at home and abroad have conducted extensive research in the field of intelligent monitoring and control for aquaculture, and have designed a number of water quality monitoring systems and intelligent feeding devices, which have realized basic functions such as data acquisition, remote transmission, and abnormal alarm[5-6]. However, most of the existing equipment is either fixed monitoring devices or single-function feeding equipment, and there are few integrated devices that deeply integrate multi-parameter water quality monitoring, automatic cruise mobility, and precise quantitative feeding; consequently, they commonly suffer from problems such as single functionality, insufficient adaptability, and limited control accuracy[7-8]. To address the above shortcomings, this paper designs an intelligent aquaculture monitoring and automatic feeding cruise system based on STM32, which integrates modules such as multi-sensor acquisition, fuzzy adaptive PID control, Bluetooth wireless communication, and automatic feeding execution, and can accomplish full-area water quality monitoring, autonomous path cruise, and timed precise feeding, thereby providing a low-cost, high-reliability intelligent solution for small and medium-sized aquaculture farms[10].

1. System Overall Design

The system adopts a modular design concept, and its overall architecture is divided into the perception layer, the control layer, the execution layer, and the application layer. The overall structure of the system is shown in Figure 1.

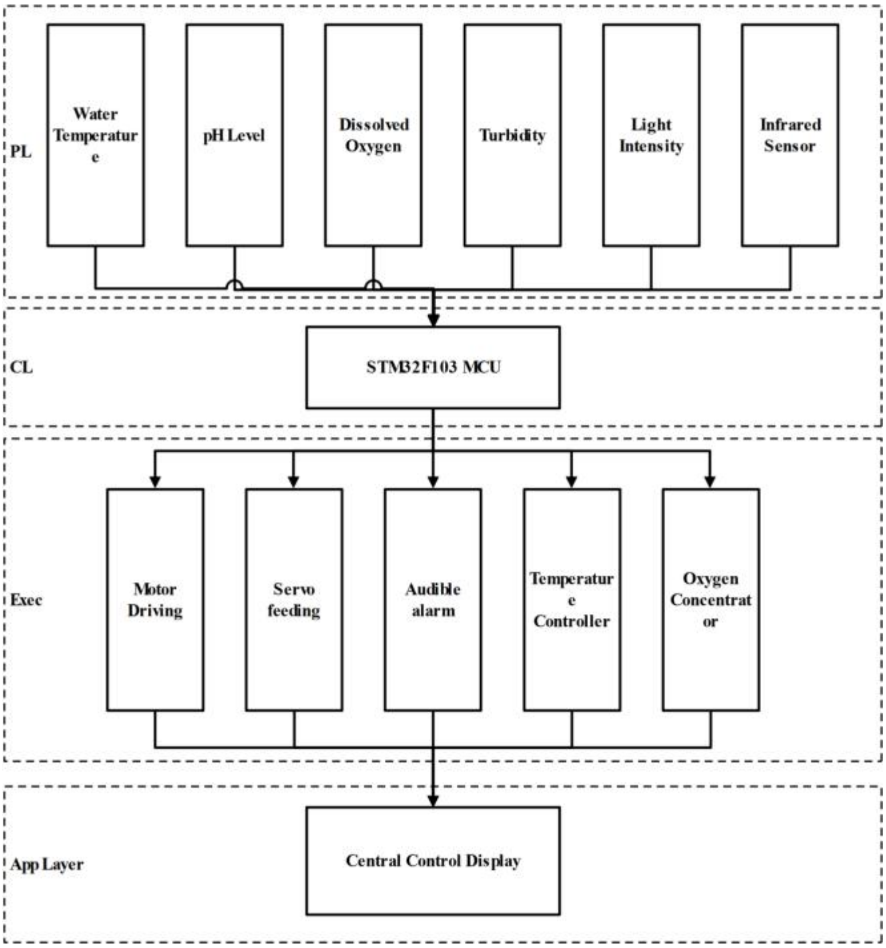

Figure 1. Block diagram of the overall system structure.

Perception layer: The perception layer is responsible for collecting environmental data from the fish pond, including parameters such as water temperature, pH value, dissolved oxygen, turbidity, and light intensity, as well as infrared sensor signals for automatic tracking. All sensor data are transmitted to the control layer via IO ports or ADC interfaces.

Control layer: The control layer, with the STM32F103 microcontroller as its core, is responsible for receiving and processing the data from the perception layer, running the PID cruise control algorithm, determining whether the water quality exceeds the preset limits, and generating control instructions according to the predefined logic. At the same time, it exchanges data with the mobile APP through the Bluetooth module.

Execution layer: The execution layer includes the L298N motor driver module and DC geared motors (which drive the wheels for movement and cruising), servos (which drive the spray feeding device), an audible and visual alarm (for abnormal alerts), as well as external devices such as thermostats and oxygen generators controlled via relays.

Application layer: Users can send remote commands (such as start/stop, feeding, and parameter modification) and receive data (real-time water quality data display) through the Bluetooth Serial Assistant APP. Meanwhile, the onboard OLED display provides localized data viewing and human-computer interaction.

2. System Hardware Design

The system hardware adopts a layered modular, highly integrated, and strong anti-interference design approach. Around the core controller, six functional units are constructed: power supply, perception, motion, feeding, communication, and display. All units are interconnected through standardized interfaces, resulting in a compact overall structure and stable operation, which can adapt to the humid, watery, and electromagnetically complex working environment typical of aquaculture scenarios. The model is shown in Figure 2.

2.1 Main Control and Power Supply Module

The main control chip adopts the STM32F103 series high-performance microcontroller, whose core is based on the ARM Cortex-M3 architecture. Its standard operating voltage is 3.3 V. The chip integrates multiple general-purpose IO ports, multi-channel high-precision ADCs, multi-purpose general timers, and multiple UART, I^2C, and RS485 communication interfaces. With abundant resource allocation, it can simultaneously support parallel processing of multiple tasks, including multi-sensor data acquisition, closed-loop motor control, servo angle adjustment, Bluetooth data transmission, and OLED display refresh. It features advantages such as high computing speed, low power consumption, and strong stability, fully meeting the control requirements of mobile intelligent aquaculture equipment[10].

The power management module adopts the LM2596 DC-DC high-efficiency step-down converter, which supports a wide-range DC voltage input from 7 V to 24 V and can stably convert the external vehicle power supply into a standard output of 5 V/3 A, thereby providing stable and reliable power supply for the main control chip, water quality sensors, servos, Bluetooth modules, and display devices. This module features over-current protection, over-voltage protection, short-circuit protection, and voltage regulation output characteristics, which can effectively solve problems such as insufficient power supply, voltage fluctuations, and noise interference that may occur when multiple modules operate simultaneously. In addition, with the secondary linear voltage regulator circuit, it further outputs 3.3 V to achieve separate power supply for digital circuits and analog circuits, significantly improving the overall operational stability of the system and the accuracy of data acquisition[11].

2.2 Environmental Perception Module

The environmental perception module assumes the dual functions of collecting water environment parameters and detecting the vehicle's position and motion status. It consists of a water quality detection unit and a cruise positioning unit, and serves as the data foundation for the system to achieve intelligent monitoring and automatic cruising.

In terms of water quality detection, the system adopts a multi-parameter collaborative monitoring scheme. For water temperature monitoring, a high-precision thermistor-type sensor is employed, with a measurement range of 0–80 ℃ and a measurement error of ≤ ±0.5 ℃, which can operate stably in aquaculture water bodies over long periods. Both the pH sensor and the dissolved oxygen sensor are industrial-grade digital probes that communicate with the main control chip via the RS485 bus, offering long transmission distances and strong anti-interference capability, and can obtain real-time data on water acidity/alkalinity and dissolved oxygen content. The turbidity sensor outputs an analog voltage signal, which can directly reflect changes in water turbidity. After acquisition, filtering, and processing by the main controller, the data from these four types of sensors form a comprehensive water quality evaluation basis, providing support for aquaculture environment regulation[2,7].

In terms of cruise perception, the system adopts an infrared tracking sensor module, which is installed at the bottom of the vehicle body. It is used to identify the preset black guide path on the ground in real time and to quickly detect the lateral deviation between the vehicle and the path. The deviation signal is fed back to the controller in real time, providing continuous and stable error input for the fuzzy PID algorithm, thereby ensuring that the vehicle travels smoothly along the preset route[12-13].

2.3 Motion Control and Feeding Execution Module

The motion control module adopts the L298N high-power motor driver board, which receives the PWM speed regulation and direction control signals from the main controller, and drives the dual DC geared motors with optical encoders to operate. A closed-loop speed control scheme is employed, in which the PID algorithm calculates and adjusts the PWM duty cycle in real time to achieve precise speed control and dynamic path correction, enabling the vehicle to maintain good stability and path-following performance under various road conditions such as straight-line driving and cornering, thereby improving the reliability and accuracy of automatic cruising[13].

The feeding actuator adopts a high-precision micro servo to drive a dedicated spray-type feeding device. The STM32 main controller outputs programmable PWM signals to precisely control the servo to rotate continuously within the range of 0° to 180°. By adjusting the servo's rotation angle and action duration, the system achieves quantitative and uniform scattering of feed. This feeding method can effectively expand the coverage area, avoid problems such as fish aggregation, local oxygen deficiency, and feed residue and waste caused by traditional fixed-point feeding, thereby improving feed utilization efficiency and enhancing the aquaculture water environment[5-6].

2.4 Wireless Communication and Display Module

For wireless communication, the BT04 Bluetooth serial module is adopted, which is directly connected to the main controller via the UART interface. The communication baud rate is configured as 9600 bps, enabling stable and reliable bidirectional data transmission with the mobile APP. On the uplink, the module can upload water quality data (such as water temperature, pH value, and dissolved oxygen) and working status in real time; on the downlink, it can receive remote control commands to perform operations such as starting or stopping cruising, manual feeding, and modifying parameter thresholds, thus meeting the short-range wireless control requirements of aquaculture farms[10].

The local display unit adopts an OLED display, which is driven via the I²C bus, with a resolution of 128×64, and features low power consumption, high contrast, and a wide viewing angle. The screen can refresh in real time and display key information such as temperature, pH value, dissolved oxygen, time, cruise mode, and feeding status, which facilitates on-site debugging, viewing, and operation for staff, and improves overall usability.

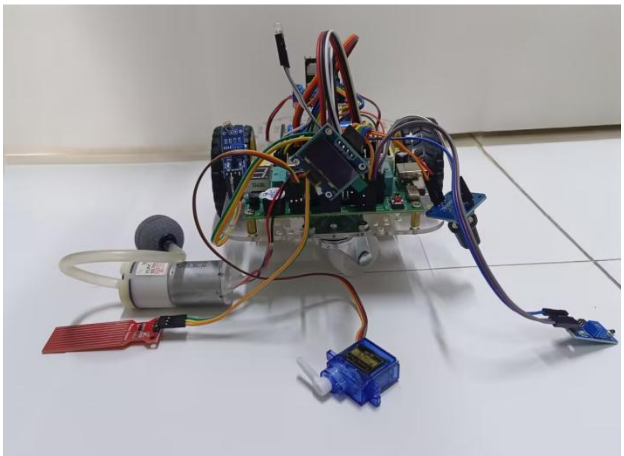

Figure 2. Model display diagram

3. System Software Design

3.1 Main Program Flow

After power-on reset, the system sequentially completes clock configuration, GPIO port configuration, ADC acquisition configuration, timer configuration, UART serial port configuration, and I²C communication configuration, and loads default configuration parameters such as feeding time, water quality thresholds, and control parameters. After completing the system startup self-test, it then enters the main loop working mode.

In the main loop, the system performs multi-task parallel processing at fixed periods: it completes water quality sensor data acquisition and digital filtering at a cycle of 100 ms, and refreshes the OLED display data at a cycle of 200 ms. At the same time, it scans key states in real time, compares the feeding schedule, runs the automatic cruise control algorithm, and parses and executes Bluetooth remote commands, thereby achieving coordinated and stable operation of all functions. It is equipped with a real-time abnormal response mechanism: once water quality parameters exceed the limits, sensor failures, or operational abnormalities are detected, it can quickly trigger alarm outputs and linked regulation to ensure the safety of the aquaculture environment. The software main program flow is shown in Figure 3.

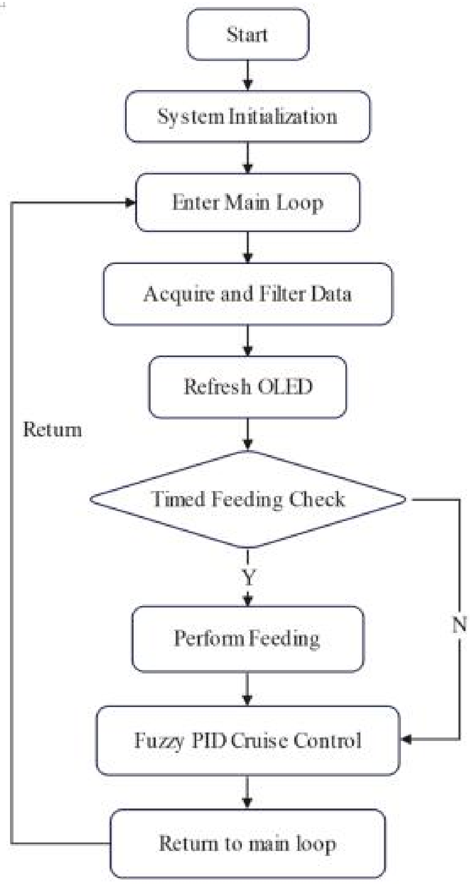

Figure 3. Flowchart of the main program

3.2 Sensor Data Acquisition and Processing

The system supports a hybrid acquisition mode for both analog and digital sensors. Water quality sensor signals are acquired in real time via ADC interfaces or serial port interrupts, respectively. To suppress data fluctuations caused by on-site electromagnetic interference, water body fluctuations, and device noise, and to improve monitoring stability, the system applies a moving average filtering algorithm to smooth consecutive groups of raw sampled data, which effectively reduces random interference and enhances data reliability[11].

For digital sensors such as pH and dissolved oxygen that adopt the RS485 interface, data interaction is performed according to the standard Modbus-RTU protocol. The main controller periodically sends query frames, and after receiving the data returned from the sensors, it performs CRC verification to ensure complete and error-free data transmission. Then, it parses the valid data bits and performs unit conversion to obtain the actual physical quantity values. For analog-output sensors such as temperature and turbidity, the system completes voltage signal acquisition through multi-channel ADCs, and converts the voltage values into corresponding engineering values based on calibration formulas, thereby providing accurate references for water quality evaluation and abnormality judgment. The multi-parameter monitoring circuit is shown in Figure 4[8].

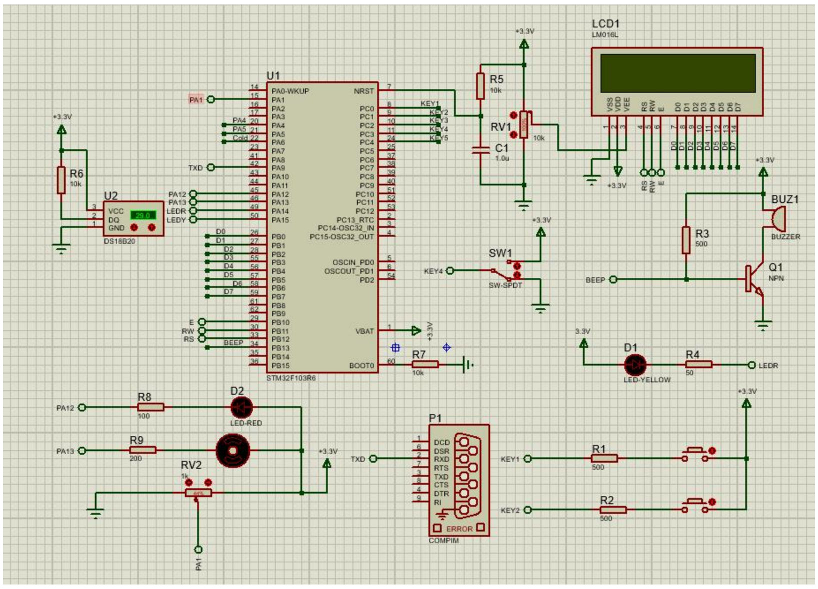

Figure 4. Multi-parameter monitoring circuit diagram

3.3 Fuzzy Adaptive PID Control Algorithm for Automatic Cruising

To enable the model to travel smoothly and accurately along the preset path, and to adapt to the actual working conditions of uneven ground and frequent interference in fish ponds, the system introduces fuzzy logic rules for dynamic parameter adjustment based on the traditional positional PID control, thereby constructing a fuzzy adaptive PID controller that significantly improves path tracking accuracy and driving stability.

The control system takes the path deviation signal e(t) detected by the infrared tracking sensor and the deviation change rate ec(t) as the dual inputs, and uses the differential control amount u(t) of the left and right motors as the output. Here, the path deviation is the lateral offset between the model center at the current moment and the preset path, and the deviation change rate reflects the real-time trend and speed of deviation variation. The discretized calculation formula is as follows:

$$e_c(t) = \frac{e(t) - e(t-1)}{T} \tag{1}$$

In Equation (1), e(t−1) is the path deviation of the previous sampling period, and T is the system control period, which is set to 100 ms in this system.

The system adopts a positional PID discrete control algorithm, and its core expression is as follows:

$$\mathrm{u}(t) = K_p e(t) + K_i \sum_{j=0}^{t} e(j) + K_d [e(t) - e(t-1)] \tag{2}$$

In Equation (2), Kp, Ki, and Kd are the proportional, integral, and derivative coefficients, respectively.

The fuzzy control stage divides the input quantities into seven fuzzy subsets: {NB, NM, NS, ZO, PS, PM, PB}, and establishes a complete fuzzy rule base of 49 rules based on the tracking control mechanism. Through Mamdani inference and center-of-gravity defuzzification, the three parameters Kp, Ki, and Kd are dynamically tuned online. When the deviation is large, the proportional coefficient is increased for rapid correction; when the deviation change rate is too fast, the derivative action is strengthened to suppress oscillation; when the system approaches steady state, the integral coefficient is optimized to eliminate steady-state error, enabling the model to quickly center on straight sections, turn smoothly at curves, and rapidly suppress disturbances on bumpy roads. Through engineering tuning and fuzzy rule optimization, the model achieves faster tracking response, smaller overshoot, and higher stability, fully meeting the path cruising requirements in aquaculture scenarios[12-13].

4. Test and Result Analysis

4.1 Test Environment and Scheme

The tests were conducted in a constant temperature and humidity laboratory environment, with the temperature controlled at 25±1 ℃ and the humidity maintained at 60±5%, so as to avoid interference from environmental factors on the test results. The test equipment includes the designed device, a professional-grade water quality calibrator (accuracy class 0.01), an infrared tracking path simulation board, a DC regulated power supply, and a data acquisition recorder.

The test scheme strictly follows the laboratory test specifications for embedded intelligent equipment, and adopts a combination of fixed-point calibration, repetitive testing, and comparative analysis. Specifically, the water quality monitoring accuracy test adopts the synchronous sampling comparison method: for each parameter, 10 consecutive sets of data are collected, and after removing extreme values, the average is taken to calculate the absolute error between the measured values of this system and those of the standard instrument. For the automatic cruise performance test, a closed-loop test track simulating a fish pond path is constructed, and both the traditional PID algorithm and the fuzzy adaptive PID algorithm designed in this paper are run separately; the core performance parameters of 10 round trips are recorded to verify the algorithm's control effectiveness.

4.2 Analysis of Water Quality Monitoring Results

For the four core parameters of aquaculture monitoring, namely water temperature, pH value, dissolved oxygen, and turbidity, standard water samples were prepared in the laboratory environment. A professional-grade water quality calibrator was used as a reference, and simultaneous comparative tests were conducted with this model. The test results are shown in Table 1.

Table 1. Comparison of multi-parameter monitoring accuracy.

Parameters	Measured Value	Standard Instrument Value	Absolute Error	Allowable Error
Water Temp（℃）	24.3	24.1	0.2	±0.5
pH	7.8	7.6	0.2	±0.3
DO（mg/L）	5.2	5.0	0.2	±0.3
Turbidity（NTU）	12.5	12.0	0.5	±1.0

The laboratory test data indicate that the absolute measurement errors of the four core water quality parameters of this model are all far less than the permissible error range for routine aquaculture monitoring, and the data are stable without any obvious drift. The moving average filtering algorithm can effectively suppress data fluctuations induced by device noise and electromagnetic interference, and the monitoring accuracy fully satisfies the daily operational needs of small and medium-sized aquaculture farms, thus confirming the reliability of the water quality acquisition and processing module.

4.3 Analysis of Automatic Cruise Performance Results

On the closed-loop test track simulating the fish pond path, typical driving scenarios such as straight lines and curves were simulated. Under the same path, the same speed, and the same initial parameters, both the traditional PID algorithm and the fuzzy adaptive PID algorithm proposed in this paper were respectively adopted to conduct 10 closed-loop cruise tests. The lateral deviation data of the path were recorded, and the control effect comparison curves were plotted using MATLAB, as shown in Figure 5.

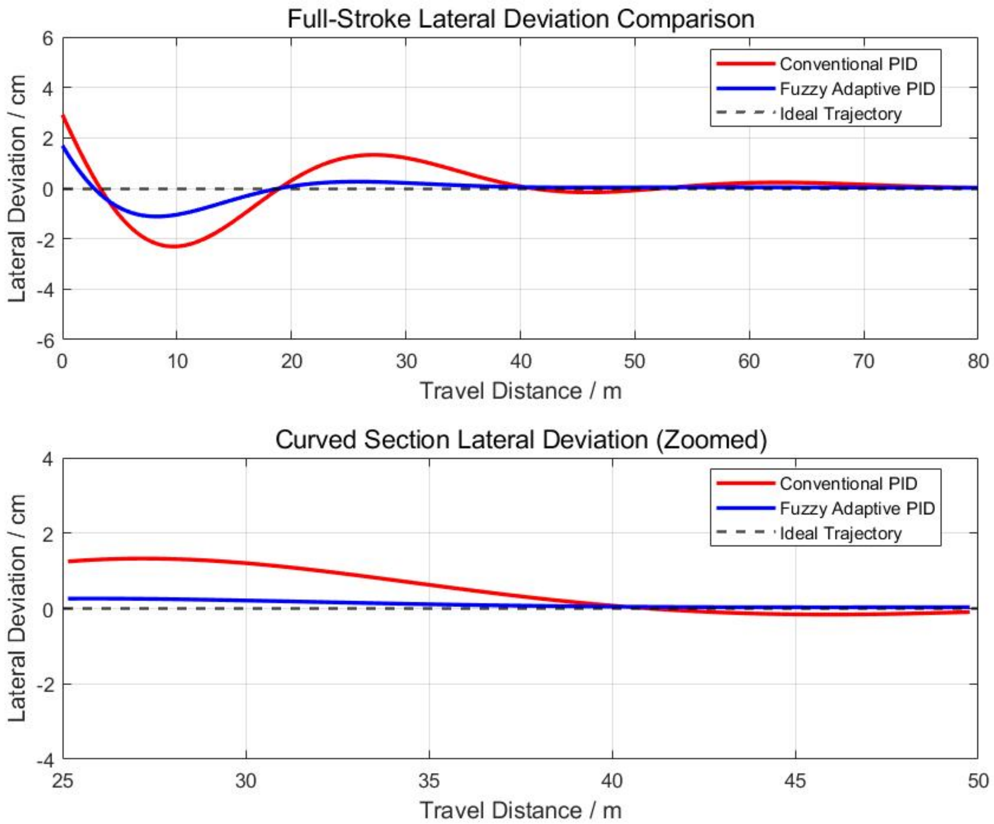

Figure 5. Comparison of control effects between traditional PID and fuzzy adaptive PID

The cruise test results show that when the traditional fixed-parameter PID algorithm was adopted, the model exhibited slight jitter on straight sections, and the path deviation at curves was relatively large, with a maximum lateral deviation of 3.2 cm and an average path deviation of 2.1 cm; the tracking success rate in 10 tests was 90%, with minor overshoot and deviation phenomena. In contrast, when the fuzzy adaptive PID algorithm was adopted, the system could dynamically adjust the control parameters according to the real-time path deviation and its change rate. The model ran smoothly without jitter on straight sections, and at curves, it turned smoothly with timely correction. The maximum lateral deviation was reduced to 1.8 cm, and the average path deviation was only 1.1 cm; the tracking success rate in 10 tests reached 100%. Both the anti-interference capability, path tracking accuracy, and driving stability were significantly improved, which verifies the superiority and rationality of the fuzzy adaptive PID control algorithm[11].

5. Conclusion

This paper, aiming at the industry pain points of low manual management efficiency, delayed water quality monitoring, poor feeding precision, and high labor costs in traditional aquaculture, and combining with the actual needs of small and medium-sized aquaculture farms, designs and implements an intelligent aquaculture monitoring and automatic feeding cruise system based on STM32. This device takes the STM32F103 as the control core, integrates five core functions, namely multi-parameter water quality monitoring, fuzzy adaptive PID automatic cruising, precise quantitative feeding, Bluetooth remote control, and abnormal alarm linkage, and adopts modular hardware and software design, featuring compact structure, controllable cost, strong anti-interference, and simple operation. Verified by targeted laboratory tests, the water quality monitoring accuracy of the device meets the aquaculture industry standards, and the fuzzy adaptive PID algorithm can achieve stable and smooth cruising along the preset path; both core functions have reached the design requirements. The device can effectively replace manual labor in routine tasks such as water quality inspection, timed feeding, and environmental monitoring, significantly reducing labor costs in aquaculture and improving management efficiency and refinement level.

This device deeply integrates mobile cruising, online water quality monitoring, and intelligent feeding, thereby solving the problems of single function, low integration, and insufficient practicality found in existing aquaculture equipment. It possesses strong innovation and practical promotion value, and can provide low-cost, high-reliability solutions for the intelligent upgrading of small and medium-sized aquaculture farms in the Northwest China region.

Fund Projects

Automatic Cruise Vehicle Integrating Monitoring and Feeding for Aquaculture Based on STM32.

Project Number: 2025339.

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