Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 20, No. 1, 2026

Design of an Intelligent Water Surface Cleaning System for Small- and Medium-Sized Water Bodies

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Abstract: To address the limitations of conventional floating waste removal methods, including high labor intensity, elevated operational risk, and insufficient adaptability to small- and medium-sized water bodies, this study proposes an intelligent water surface cleaning system for such environments. The system employs the STM32F407 as the core control unit and integrates vision, attitude, ultrasonic, and turbidity sensors to establish functional modules for environmental perception, target recognition, obstacle detection, and water quality monitoring. In the software design, a collaborative architecture between the host computer and the lower-level controller is adopted, together with a front-end/back-end separation framework, to support data transmission, status visualization, historical record management, and basic interactive functions. This scheme provides a system-level implementation path for floating waste identification, obstacle avoidance, and cleaning tasks, and may serve as a reference for the development of cleaning equipment for small- and medium-sized water bodies, thereby contributing to the maintenance of aquatic surface ecology.

Keywords: Water Surface Cleaning System; Multi-Sensor Integration; STM32F407; Human–Computer Interaction.

1. Introduction

With continued socioeconomic development, human activities have increasingly affected the ecological environment, making water quality an important public concern. Small water bodies are often covered with floating debris such as plastic bottles, foam, and decayed leaves. Without timely cleaning, these pollutants can degrade water quality and visual appearance. In larger water bodies, floating waste may also threaten aquatic ecology, landscape quality, and navigation safety[1].

Current water surface cleaning mainly depends on manual collection or large cleaning vessels. The former is labor-intensive, inefficient, and risky, while the latter is costly, bulky, and unsuitable for small water bodies. To address these limitations, this paper proposes a multi-sensor intelligent water surface cleaning system based on STM32F407. By integrating vision, turbidity, and attitude sensors, the system supports floating waste recognition, cleaning, and remote monitoring. It is intended for small- and medium-sized waters such as rivers and landscape lakes, and can provide a reference for related equipment development and future function expansion[2].

2. Overall System Design

(1) System Structure

The system is organized using a three-layer architecture, consisting of the information acquisition layer, the data processing layer, and the interactive presentation layer, as shown in Figure 1. The information acquisition layer is composed of a vision sensor, an ultrasonic sensor, a turbidity sensor, and an attitude sensor, and is primarily responsible for the real-time acquisition of floating waste images and environmental parameters of the water body. This layer provides relatively complete raw data for subsequent analysis and serves as the foundation for the stable operation of the system. The data processing layer is responsible for computing and analyzing the information collected at the front end. It employs deep learning algorithms to accomplish waste target recognition and category classification, while also recording and storing the processing results. The interactive presentation layer is mainly designed to meet user-side requirements. It is used to display the water surface condition, cleaning results, and related operational information, while also supporting real-time viewing of environmental data, historical operation record queries, as well as visualization and classified management of data.

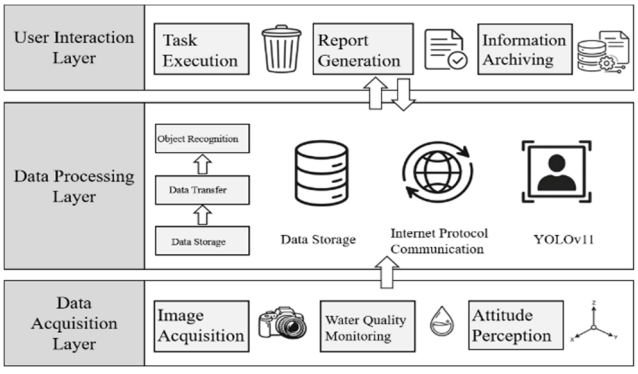


Figure 1. Overall architecture of the water surface cleaning system

(2) System Workflow

The power supply system provides stable electrical power for the entire robotic system, ensuring the normal operation of multiple sensors and enabling the real-time acquisition of key data such as system attitude stability and water quality parameters. A camera is mounted above the robot by means of a bracket to capture water surface images in real time, and the YOLOv11 object detection algorithm is employed to detect floating waste on the water surface in real time. All collected data are transmitted to the main controller. After comprehensively analyzing and processing the various types of information, the main controller sends control commands to the execution system, which regulates the servos and

propellers to realize the robot's movement on the water surface and complete the collection and removal of waste [3]. The workflow is shown in Figure 2.

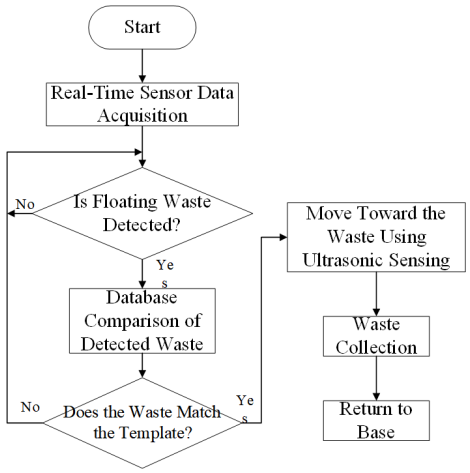


Figure 2. System workflow

3. Hardware Design

The water surface cleaning system is determined by the interaction among the robot, the operational target, and the working environment. The hardware architecture of the robot designed in this study mainly consists of a control system, a sensor system, an execution system, and a power supply system.

The control system adopts the STM32F407 as the core controller, which is responsible for sensor data acquisition, basic computation, and the control of actuators. The sensor system includes a camera sensor, turbidity sensor, attitude sensor, and ultrasonic sensor, which together enable waste target recognition, environmental state perception, obstacle detection, and attitude information acquisition. The execution system mainly comprises a propulsion module and a collection module, which undertake motion control and floating waste collection tasks, respectively. The power supply system utilizes a model-grade lithium battery to provide energy for the entire platform.

These modules operate in coordination around the task of floating waste removal on the water surface, collectively forming the hardware foundation of the system. The schematic diagram is shown in Figure 3.

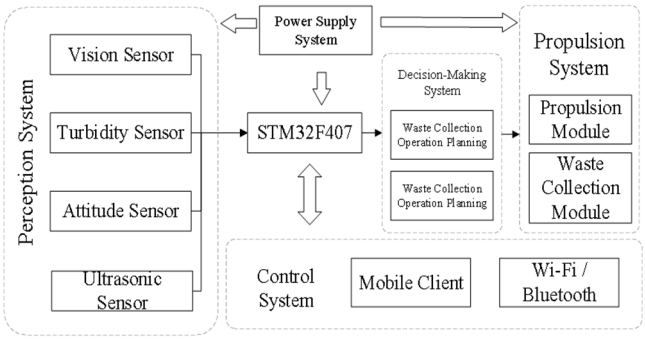


Figure 3. Overall circuit design

(1) Microcontroller Selection

As shown in Figure 4, the system adopts the STM32F407 as the main control chip. This chip is based on the Arm Cortex-M4 core, with a maximum clock frequency of 168 MHz. It features floating-point computing capability and supports DSP instructions, thereby meeting the real-time requirements of tasks such as motion control, attitude estimation, and multi-sensor data processing. In addition, the STM32F407 provides relatively abundant on-chip resources and integrates multiple communication interfaces, including UART, SPI, I2C, and CAN, which facilitates connection with the vision module, attitude sensor, ultrasonic sensor, and host computer communication module. Considering overall performance, power consumption, development maturity, and system expansion requirements, the selection of this chip provides a relatively stable control foundation for the entire system.



Figure 4. STM32F407 microcontroller

(2) Vision Sensor

To meet the practical requirements of the water surface cleaning robot in the visual recognition stage, this study selects the K230 as the vision processing chip. Compared with the main control unit, the vision side is required to undertake computational tasks such as image preprocessing, feature extraction, and object detection, and therefore imposes higher demands on parallel processing capability.

The K230 adopts a dual-core Xuantie C908 RISC-V architecture and integrates vision-related computing units, enabling it to perform the major computations required for edge-side recognition. In addition, the chip is equipped with image preprocessing capability, allowing denoising and correction of raw images captured by the camera, thereby improving input quality and reducing the interference of complex water surface environments with recognition results. In terms of power management, the K230 employs dynamic voltage and frequency scaling (DVFS) technology, which can dynamically adjust the operating frequency and power mode according to the workload of waste recognition tasks, thus meeting the requirement for long-duration continuous operation of the water surface cleaning robot.

(3) Ultrasonic Sensor

During operation, the robot must actively avoid obstacles to ensure the safety and stability of the cleaning process. In this system, the HC-SR04 ultrasonic sensor is selected as the core component for obstacle detection[4]. This sensor operates based on the principle of ultrasonic reflection. It mainly consists of a transmitting unit, a receiving unit, and a control circuit. By emitting ultrasonic waves and receiving the reflected echoes after they encounter an obstacle, the sensor calculates the distance to the obstacle according to the wave propagation time.

The core formula for distance measurement is:

$$d = \frac{1}{2}vt \tag{1}$$

where d represents the actual distance between the sensor and the obstacle, v denotes the propagation velocity of ultrasonic waves in air (approximately 340 m/s at room temperature and can be calibrated according to ambient temperature), and t represents the total time required for the ultrasonic signal to travel from emission to reception of the reflected echo.

During the operation of the HC-SR04, the main controller

first sends a trigger signal (a high-level pulse longer than 10 μs). The transmitting unit then emits a 40 kHz ultrasonic pulse. When the ultrasonic wave encounters obstacles such as floating debris on the water surface or shoreline structures, reflection occurs. After the receiving unit detects the reflected echo, it outputs a high-level signal with a duration corresponding to the echo return time. The main controller obtains the value of t through a timing module, and the obstacle distance can then be calculated using the above formula.

(4) Inertial Measurement Unit (IMU)

To ensure the attitude stability of the water surface cleaning robot during operation and to prevent attitude deviation caused by water surface fluctuations and variations in operational load, the MPU6050 sensor is selected in this system to perform real-time attitude estimation. This sensor integrates a three-axis accelerometer and a three-axis gyroscope. Its core working principle is to acquire the robot's linear acceleration and angular velocity signals and, in combination with an attitude estimation algorithm, convert the raw sensor data into three key attitude parameters: pitch, roll, and yaw[5], thereby enabling seamless interfacing with the main control chip.

The MPU6050 is equipped with a built-in Digital Motion Processor (DMP). During operation, the MPU6050 continuously reads the quaternion parameters calculated by the DMP, as shown in Equation (2), and obtains the Euler angles through Equation (3).

$$q = q_0 + q_1 i + q_2 j + q_3 k \tag{2}$$

$$\begin{bmatrix} \theta \\ \varphi \\ \psi \end{bmatrix} = \begin{bmatrix} \arctan\left[\dfrac{-2(q_1 q_2 - q_0 q_3)}{q_0^2 - q_1^{\,2} + q_2^{\,2} - q_3^{\,2}}\right] \\ \arcsin\left[2(q_2 q_3 + q_0 q_1)\right] \\ \arctan\left[\dfrac{-2(q_1 q_3 - q_0 q_2)}{q_0^2 - q_1^{\,2} - q_2^{\,2} + q_3^{\,2}}\right] \end{bmatrix} \tag{3}$$

where q represents the quaternion, and i, j and k denote three mutually orthogonal unit vectors. θ represents the yaw angle, φ represents the pitch angle, and φ represents the roll angle.

(5) Turbidity Monitoring Module

The robot employs the TS-300B turbidity sensor to detect water turbidity on the surface, thereby providing reliable data support for water quality monitoring. Its operating principle is based on light scattering theory and the Lambert–Beer law, and the measurement is performed using the 90-degree light scattering method. The sensor integrates a near-infrared LED light source with a wavelength of approximately 850 nm and a photodiode. When light passes through the water, it is scattered by suspended particles such as floating waste and sediment, and the intensity of the scattered light in the perpendicular direction exhibits an approximately linear relationship with particle concentration. The photodiode captures the scattered light signal, which is then amplified and filtered before being converted into an analog voltage output of 0.5–2.5 V. Through ADC sampling and calibration by the main controller, the signal is transformed into a standard turbidity value in NTU. The sensor adopts a ratio measurement method based on scattered light and transmitted light, with a response time of no more than 500 ms. It features low power consumption, a compact structure, and an anti-fouling probe package, making it suitable for complex water surface environments [6].

(6) Motor Module

In this system, DC motors are employed as the robot's motion actuators, and motor driving and speed regulation are realized through PWM modulation, thereby enabling basic movements such as forward motion and steering. The driving circuit adopts the L298N module, while the main control microcontroller outputs control signals to independently drive two DC motors. Considering that the robot needs to adjust its motion state in a timely manner according to the target position during actual operation, the main control unit outputs corresponding control variables after the visual recognition result is triggered, so as to change the motor speed and rotation direction and enable the robot to perform the predetermined actions. To improve motion stability, a PID closed-loop control strategy is introduced into the control process to correct the motor operating state in real time, thereby reducing speed fluctuations and attitude deviations.

4. Software Design

(1) Overall Software Design

The software design is centered on data transmission, information management, device control, and user interaction. The data transmission function is mainly responsible for information exchange among hardware units as well as between the host computer and the lower-level controller, so as to ensure that data can be acquired and invoked in a timely manner during system operation. The information management function is used to store data such as waste categories, water quality parameters, device attitude, and cleaning records, thereby providing a basis for subsequent query, statistical analysis, and data evaluation. The device control function is primarily responsible for monitoring and regulating the operating status of the cleaning device. The user interaction function, in turn, undertakes tasks such as operational information display, parameter setting, and device manipulation. These functions cooperate with one another at the software level and jointly support the system's monitoring, control, and management processes.

(2) Host–Lower Controller Communication

The system adopts a hierarchical host computer–lower-level controller architecture to realize data interaction and process control. The lower-level controller, centered on the STM32, is responsible for sensor data acquisition, basic data processing, and the execution of control logic. The host computer serves as the interaction terminal and undertakes tasks such as status display, data analysis, and the issuance of control commands. Communication between the two is implemented through the CAN bus. The lower-level controller encapsulates the sensor data, after signal conditioning and A/D conversion, into CAN communication frames and transmits them to the host computer.

The host computer software is developed based on a visual interface, which can update key parameters such as sensor monitoring values in real time and display their variation in the form of curves, while also accomplishing user interaction and command transmission. To reduce the influence of noise interference on data quality, amplitude-limiting filtering and adaptive filtering methods are introduced in the processing stage, thereby improving the stability and real-time performance of the communication process and enhancing the overall operational reliability and controllability of the

system[7].

(3) Front-End and Back-End Development

The system is implemented using a front-end/back-end separation architecture. The front end is developed based on React, with the Context API employed for global state management, and is mainly responsible for functions such as environmental parameter display, historical record query, and device control. The page layout is constructed using HTML and CSS, while the interactive components are implemented in JavaScript, enabling the system to maintain a basically consistent user experience across different terminals. For this study, such an implementation approach helps integrate monitoring information display and operational control into a unified interface.

The back end is developed based on Node.js, with Express used to build the interface service, and the data interaction between the front end and back end is organized in a RESTful manner[8]. The back end is responsible for receiving and processing relevant data such as turbidity and attitude information, while also handling front-end request responses and control command transmission. MySQL is used for persistent data storage in the system, mainly preserving user information, device status, and cleaning records.

(4) Database Design Based on MySQL

The system adopts MySQL for data management. Based on SQL, MySQL enables structured data storage and management, and supports transaction processing, index optimization, and multi-user concurrent access control, thereby satisfying the storage requirements of structured data such as device status information and waste cleaning records. Compared with commercial databases, MySQL offers lower deployment cost and greater configuration flexibility. It also demonstrates strong compatibility with back-end frameworks such as Node.js and Express, making it possible to rapidly build efficient data interaction interfaces. In addition, MySQL supports data backup and recovery mechanisms, which enables the system to meet the project requirements for lightweight implementation, high efficiency, and cross-platform compatibility [9].

5. Conclusion

This study addresses the demand for floating waste removal in small- and medium-sized water bodies by conducting systematic research on perception, control, communication, and interaction, and by constructing an intelligent water surface cleaning system integrating waste recognition, obstacle detection, attitude monitoring, water quality acquisition, and status management. Overall, the system demonstrates strong task-oriented design in terms of module coordination and functional organization, and may provide a useful reference for the research and application of cleaning equipment for small- and medium-sized water bodies. In future work, the system can be further improved in terms of functional configuration, operational coordination, and overall performance according to different operating environments, so as to enhance its engineering applicability and provide new support for green and low-carbon development.

Acknowledgments

The authors gratefully acknowledge the financial support from National College Students' Innovative Entrepreneurial Training Plan Program of North China University of Science and Technology (202510081015).

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