Design and Implementation of an Intelligent Monitoring and Management System for Used Clothing Recycling Bins Based on STM32 and WeChat Mini Program

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Abstract: This paper addresses the issues of poor management and delayed recovery in the old clothing recycling process by designing and implementing a monitoring and management system for recycling bins based on STM32 microcontroller, sensor technology, and WeChat Mini Program. The system integrates DHT11 temperature-humidity sensor, MQ-2 smoke sensor, HC-SR04 ultrasonic sensor, and HX711 weight sensor to achieve real-time monitoring of internal environmental conditions and clothing accumulation status within recycling bins. Leveraging Wi-Fi communication technology, the system transmits data to the WeChat Mini Program platform, enabling remote status monitoring and abnormal alarm notifications for management personnel. Experimental results demonstrate the system's stable operation, with advantages including low cost, low power consumption, and intelligent management capabilities. This solution provides an efficient and intelligent approach for old clothing recycling management, exhibiting promising application prospects in promoting resource recycling and environmental protection.

Keywords: Old clothing recycling; STM32 microcontroller; Wi-Fi communication technology

1. Introduction

With the vigorous development of the e-commerce industry, the turnover rate of clothing consumption has accelerated, leading to a continuous increase in the amount of discarded old clothing. However, there are numerous issues with the current recycling of old clothing, such as delayed collection from recycling bins and inefficient management, resulting in resource waste and environmental pollution. This study aims to design and implement an IoT-based monitoring and management system for old clothing recycling bins. By integrating single-chip microcomputers, sensors, and WeChat mini-programs, it addresses the pain points in the management of old clothing recycling bins, enabling real-time monitoring, intelligent early warning, and efficient management. This reduces management costs and provides new ideas and technical support for the standardization and intelligent development of the old clothing recycling industry. The development of this system is beneficial for improving the recycling efficiency of old clothing and promoting the recycling of resources. It not only holds significant theoretical value but also has remarkable social and environmental benefits, playing a crucial role in driving the standardization and intelligent development of the old clothing recycling industry.

1.1 Research Purpose and Significance

With the vigorous development of the e-commerce industry, the turnover rate of clothing consumption has accelerated, leading to a continuous increase in the amount of discarded old clothing. However, there are numerous issues with the current recycling of old clothing, such as delayed collection from recycling bins and inefficient management, resulting in resource waste and environmental pollution. This study aims to design and implement an IoT-based monitoring and management system for old clothing recycling bins. By integrating single-chip microcomputers, sensors, and WeChat mini-programs, it addresses the pain points in the management of old clothing recycling bins, enabling real-time monitoring, intelligent early warning, and efficient management. This reduces management costs and provides new ideas and technical support for the standardization and intelligent development of the old clothing recycling industry. The development of this system is beneficial for improving the recycling efficiency of old clothing and promoting the recycling of resources. It not only holds significant theoretical value but also has remarkable social and environmental benefits, playing a crucial role in driving the standardization and intelligent development of the old clothing recycling industry.

1.2 Domestic Research Status

In recent years, with the enhancement of public environmental awareness and the popularization of resource reuse concepts, there have been abundant research achievements in domestic old clothing recycling systems, mainly focusing on three directions: improvement of recycling methods, application of new technologies, and the establishment of management mechanisms.

In terms of recycling model innovation, Wei Dan (2021) constructed a full-process model for old clothing recycling, processing, and reuse, emphasizing the impact of user participation and operational convenience on efficiency. His intelligent recycling station scheme laid the foundation for technological development [1]. The team led by Lu Xiangyang (2020) empirically pointed out that 78% of recycling sites were managed irregularly and proposed a government-enterprise collaboration model that increased the recycling efficiency of pilot sites by 40% [2]. Chen Yuangang compared differences between urban and rural communities and proposed a three-tier node service system in rural areas, which improved the recycling efficiency by 34%. His incentive system of exchanging waste for goods provided practical reference for the points feature of the mini-program [5]. Qin Xueying emphasized the importance of community participation in the sustainable development of old clothing recycling [6].

At the technological application level, the team led by Jiang Tao (2022) confirmed through life cycle assessment that the closed-loop recycling system of brand enterprises could reduce emissions by 2.3 tons per ton of old clothing, clarifying the environmental value of waste clothing recycling [3]. Yuan Ying designed an intelligent recycling bin for campuses based on NB-IoT technology, enabling data monitoring and early warning [4]. Zheng Jiaxin constructed a multi-indicator classification model for old clothing materials with an accuracy rate of 89.2%. Her achievements can be applied to the data verification of weight sensors, the adjustment of smoke alarm thresholds, and the selection of equipment performance [7]. Liu Yu'ang et al. utilized IoT technology to achieve real-time monitoring and intelligent management of recycling bins [15].

In management mechanism research, Hu Ting pointed out that the management system for old clothing recycling bins was imperfect and the responsible entities were unclear, necessitating strengthened daily management and supervision [8]. The team led by Hu Aofan determined the pressure threshold of the old clothing compression device and the bin body material through simulation, providing a basis for equipment material selection [9]. Yu Jia believed that the public had insufficient awareness of old clothing recycling and suggested strengthening publicity and education [10]. Li Kuan proposed three principles for the locality design of old clothing recycling bins, emphasizing the error-tolerant space of the operation interface and explaining the necessity of using an OLED display screen in the system [11].

Currently, domestic research on old clothing recycling management systems has evolved from a single-mode to a multi-faceted and systematic approach. However, issues such as low recycling efficiency and insufficient public participation still persist. In the future, with technological innovation and policy support, it is expected to further improve recycling management efficiency and sustainability.

1.3 Foreign Research Status

Foreign research in the field of old clothing recycling management systems has formed a comprehensive system, with research focuses on three major directions: the application of intelligent technologies, the development of chemical recycling processes, and environmental sustainability assessment.

In terms of the development of chemical recycling processes, relevant research has given waste old clothing a second life, effectively promoting the development of the circular economy and significantly reducing environmental hazards. For example, the intelligent kitchen waste bin designed by the Yeo research team utilizes anaerobic fermentation technology to convert organic waste into electricity, generating 0.38 kilowatt-hours of electricity per kilogram of waste processed. They also pointed out that assessing the environmental benefits of IoT devices requires consideration of hidden costs. This finding prompted the adoption of the Deep-sleep mode of the ESP8266 module in this system to reduce equipment standby energy consumption [12]. Shailey et al. explored the feasibility of chemical recycling of waste old clothing, believing that this method could reduce the demand for new raw materials, lower carbon emissions, and assist the fashion industry in its environmental transformation [14].

There have been abundant achievements in the application of intelligent technologies. Harjoseputro et al. designed an IoT-based intelligent waste recycling bin that integrates a microcontroller and multiple sensors. It can convert organic waste into liquid fertilizer and can be controlled through a smartphone application [13]. Karmaker et al. developed an intelligent garbage monitoring and alarm system that uses sensors to monitor the waste level in garbage bins and transmits data via Wi-Fi. They also developed an Android application for real-time monitoring and management [16].

In terms of environmental sustainability assessment and management optimization, Zhou et al. introduced a behavioral economics perspective and found through AB testing that the dynamic incentive algorithm community (adjusting point rewards based on residents' historical disposal amounts) had a 41% higher recycling volume than the fixed-point incentive community. Their game theory model indicated that user participation would significantly increase when users perceived increasing marginal benefits. These studies demonstrate that intelligent technologies not only improve waste treatment efficiency but also enhance system traceability and management convenience [17].

The research achievements of foreign countries in the intelligentization, chemical recycling, and public incentive aspects of old clothing recycling management systems provide valuable experience and technical references for the development of this field in China.

2. Hardware Selection for the Old Clothing Recycling Bin Monitoring and Management System

This system adopts a modular architecture for hardware design, with the STM32F030C8T6 single-chip microcomputer as the core controller. It connects various functional modules through standard interfaces, including sensor modules, communication modules, actuators, and human-machine interaction modules. The system is powered by 5V DC and converts it to 3.3V through an LDO voltage regulator chip to supply power to the single-chip microcomputer and some modules.

2.1 Core Controller: STM32 Single-Chip Microcomputer

In embedded system development, the selection of the STM32 single-chip microcomputer takes into account key factors such as performance, real-time capability, and cost.

In the system for monitoring and managing old clothing recycling, the simultaneous operation of multiple sensors places high demands on data acquisition accuracy and the number of interfaces. The STM32 features a 12-bit ADC and is equipped with multiple UART and SPI interfaces, which precisely meet the requirements. In contrast, the Arduino has only a 10-bit ADC and insufficient interfaces, and it may be overloaded and fail to work properly when handling complex tasks. Although the ESP32 comes with a built-in wireless module, its driver is too complex and it consumes a large amount of power. In medium- and short-distance fixed scenarios, this becomes a disadvantage. The STM32 has an extremely fast interrupt response speed, taking less than 5 microseconds to react. Its hardware PWM module (TIM2) can precisely control stepper motors, ensuring high stability and accuracy. The Raspberry Pi Pico relies on software simulation for PWM, which is inferior in this regard and has difficulty guaranteeing control accuracy. The STM32 is not only rich in peripherals but also affordable, with a cost only 60% of that of the ESP32. Moreover, it supports the FreeRTOS system, enabling easy implementation of multi-task concurrent operation. If new functions, such as adding a sensor or optimizing data processing, are to be added to the system in the future, the STM32 allows for convenient expansion without the need for extensive redesign.

2.2 Temperature and Humidity Sensor: DHT11

In the design of the environmental monitoring system for old clothing recycling bins, after comprehensive consideration of environmental adaptability, hardware resources, and cost, the DHT11 temperature and humidity sensor was finally selected.

The connection scheme between the sensor and the main control chip is as follows: The VCC and GND pins of the DHT11 are connected to the 5V power supply and ground respectively to construct a power supply circuit. The DATA pin is connected to the PA1 pin of the STM32 for data transmission. The PA1 pin is also reused as a backup ADC input channel, and different functions are coordinated through a time-division multiplexing mechanism, effectively improving the utilization rate of hardware resources.

2.3 Smoke Sensor: MQ-2

In the design of the safety monitoring system for old clothing recycling bins, after comprehensive consideration of gas detection requirements, integration flexibility, and cost, the MQ-2 combustible gas sensor was selected.

During hardware connection, the VCC and GND of the MQ-2 are connected to the 5V power supply and ground respectively. The AO pin is connected to the PB1 of the STM32 for signal acquisition, and the DO pin is not currently used, reserving an interface for system function upgrades.

2.4 Ultrasonic Sensor: HC-SR04

In the design of the capacity monitoring module for old clothing recycling bins, after comprehensive evaluation of measurement range, hardware adaptability, and cost, the HC-SR04 ultrasonic sensor was selected. As shown in Table 1.

Table 1: Detailed Comparison of Ultrasonic Sensor Selection.

Device	HC-SR04	US-100	JSN-SR04T
Measurement Range	2cm-400cm	2cm-450cm	20cm-600cm
Accuracy	±3mm (static)	±1mm(static)	±5mm (dynamic)
Interface Type	Digital pulse (Trig/Echo)	UART/TTL level Analog	Analog signal/Serial port
Operating Voltage	5V	3.3V-5V	5V
Cost	￥8-12	￥20-25	￥15-20

When connecting the sensor to the STM32, the VCC is connected to the 5V power supply, the GND is grounded, the Trig pin is connected to the PB7 to send trigger pulses, and the Echo pin is connected to the PA12 to receive echo signals, enabling real-time monitoring of the clothing height.

2.5 Weight Sensor: HX711

In the selection of the weight sensor, considering factors such as range, hardware complexity, and cost, the HX711 weighing sensor module was selected. When connecting, the VCC of the module is connected to the 3V power supply, the GND is grounded, the SCK is connected to the PA7 of the STM32 for data reading, and the SDA is connected to the PA15 to send clock signals.

2.6 WiFi Communication Module: ESP8266

In the selection of the WiFi communication module, considering factors such as the deployment environment, hardware complexity, and cost control, the ESP8266 was finally determined as the wireless communication module. Recycling bins are mostly placed in communities, campuses, and other areas covered by WiFi networks. In actual hardware connection, the VCC pin of the ESP8266 module is connected to the power supply for power supply, and the GND pin is grounded to form a complete circuit. The RXD2 pin is connected to the USART2_TX pin of the STM32 to receive control instructions sent from the cloud. The TXD pin is connected to the USART2_RX pin of the STM32 to upload the data collected by the sensors.

2.7 Buzzer Alarm Module

In the selection of the buzzer, considering factors such as sound pressure requirements, driving complexity, and cost, a piezoelectric buzzer was finally selected as the alarm sound-producing device.

In terms of hardware connection implementation, the buzzer alarm module adopts a typical transistor driving circuit: The positive terminal of the buzzer, BEEP, is connected to the collector of an NPN transistor Q4 through a 1kΩ current-limiting resistor R11, and the emitter of the transistor is grounded to form a circuit. The negative terminal of the buzzer is directly grounded. This connection method can effectively achieve the driving control of the buzzer by the STM32.

2.8 OLED Display Screen

In the selection of the display module, considering factors such as display performance, power consumption, and hardware adaptability, the SSD1306 OLED display screen was selected. Its 128×64 resolution supports a graphical interface, which can present monitoring data such as temperature, humidity, and weight more intuitively compared to the 1602 LCD, which can only display characters.

The specific connections between the OLED display screen and the STM32 are as follows: VCC and GND are connected to the power supply and ground respectively for power supply. SCK and SDA are connected to the PB6 and PB7 of the STM32 for communication. The RST and DC pins are connected to the PC13 and PC14 respectively to achieve reset and data mode control.

2.9 Stepper Motor Bin-Closing Module

In the selection of the stepper motor driving module, considering factors such as motor adaptability, control requirements, and cost, the ULN2003 driving module was selected. The specific connections between the stepper motor and the STM32 are as follows: The input pins A - D of the driving module are connected to the PC13, PC14, PC15, and PB9 of the STM32 respectively to control the power-on sequence of the motor windings. VCC is connected to the power supply, and GND is grounded to form a complete circuit.

2.10 Water Pump Spray Fire-Extinguishing Module

In the selection of the water pump driving module, considering factors such as driving performance, control requirements, and cost, the TC1508S module was selected. The specific connections between the TC1508S module and the STM32 are as follows: The control pin Pi of the module is connected to the PB4 of the STM32 to receive start-stop signals. VCC and GND are connected to the power supply and ground respectively, and the water pump interface is directly connected to the positive and negative poles of the water pump to complete the driving.

3. Design of the Software System for the Used Clothing Recycling Monitoring and Management System

3.1 Software System Architecture Design

The software architecture of the used clothing recycling monitoring and management system adopts a layered design approach, divided into data acquisition, data transmission, data processing, and application presentation. The system follows a modular development philosophy, enabling the coordinated operation of various functional modules through standardized interfaces, effectively enhancing the system's scalability and ease of maintenance.

The data acquisition layer serves as the system's sensory organ for external information, responsible for the real-time acquisition of recycling bin status data. This layer utilizes hardware devices such as temperature and humidity sensors, ultrasonic ranging modules, smoke sensors, and weighing sensors to collect key data in real time, including internal temperature and humidity, clothing fill level, combustible gas concentration, and weight. The collected data undergoes preliminary processing and format conversion in a microcontroller to ensure compliance with subsequent transmission and processing requirements, achieving direct software-hardware interaction.

The data transmission layer is built upon the ESP8266 WiFi communication module and employs the MQTT protocol for remote data transmission. Renowned for its lightweight nature, the MQTT protocol offers low bandwidth consumption and fast real-time response, making it highly suitable for IoT device communication needs. In system design, a rigorous data packet structure and transmission mechanism have been established, with meticulous consideration given to data validation and retransmission strategies, ensuring comprehensive data integrity and reliability during transmission and providing stable data support for upper-layer data processing and applications.

3.2 IoT Cloud Platform Design

The system selects Tencent Cloud IoT Development Platform due to its support for large-scale device access, data storage, and real-time analysis, offering comprehensive device management and message forwarding services.

Functional design encompasses data storage, data analysis, and device management. Historical data such as temperature, humidity, and smoke concentration are stored using a time-series database (TSDB). Remote configuration of sensor thresholds and monitoring of device working status are supported.

The communication protocol employs MQTT, with the ESP8266 module uploading sensor data to the Tencent Cloud IoT Development Platform and the WeChat mini-program.

3.3 WeChat Mini-Program Design

The WeChat mini-program on mobile devices provides convenient mobile access, allowing users to check the status of used clothing recycling bins anytime, anywhere.

Developed using the MINA framework, the WeChat mini-program features a simple and intuitive interface design, primarily comprising the following functional modules:

Real-time Data Viewing Interface: After the hardware devices are connected to the network and the WeChat mini-program interface is launched, administrators can view real-time data from various sensors, including temperature and humidity data, ultrasonic ranging data, smoke concentration, and clothing weight.

Threshold Setting Interface: Provides sliders for administrators to adjust various alarm thresholds based on current environmental changes, including upper and lower limits for temperature and humidity, smoke concentration thresholds, remaining volume reminder thresholds, and weight reminder thresholds.

Automatic/Manual Mode Switching: Administrators can change the program mode in the WeChat mini-program, selecting between automatic and manual program startup modes.

3.4 System Program Design

3.4.1 Temperature and Humidity Acquisition Module (DHT11)

The code function of the temperature and humidity acquisition module is to implement single-bus protocol communication, completing the acquisition and validation of temperature and humidity data.

3.4.2 Smoke Detection Module (MQ-2)

The function of the smoke detection module is to perform ADC acquisition of analog signals, calculate smoke concentration, and trigger threshold alarms.

3.4.3 Ultrasonic Ranging Module (HC-SR04)

The core function of the ultrasonic ranging module is pulse triggering and echo capture, calculating clothing pile height and deducing remaining height.

3.4.4 Weight Monitoring Module (HX711)

The core function of the weight monitoring module is to read 24-bit ADC data via the SPI protocol and convert it into actual weight values.

4. System Functional Testing

System functional testing is a crucial step in ensuring the practical application effectiveness of the used clothing recycling bin monitoring and management system. Its core objective is to comprehensively inspect whether each functional module of the system can meet the expected design indicators, ensuring that the system can operate stably, reliably, and accurately in real-world usage scenarios. Through systematic functional testing, various hidden issues within the system can be promptly identified and resolved, aligning system functions closely with actual user needs and laying a solid foundation for subsequent promotion and application.

4.1 Temperature and Humidity Monitoring Function Testing

During the functionality test of the DHT11 sensor, the temperature and humidity sensor was first placed in a simulated environment where different temperature and humidity values were manually set. The microcontroller then read the data collected by the sensor and uploaded it to the WeChat mini-program via the communication module. Managers could directly view real-time temperature and humidity data on the WeChat mini-program interface. Meanwhile, pre-set temperature and humidity thresholds were established in the system. When the environmental temperature and humidity exceeded the set range, the buzzer's ability to promptly emit an alarm signal was observed to verify the effectiveness of the temperature and humidity monitoring and alarm functions. The specific test steps are outlined in Table 2 Temperature and Humidity Monitoring Function Testing.

Table 2: Temperature and Humidity Monitoring Function Testing.

Test Scenario	Set Temperature/ Humidity	Threshold Range	Expected Result	Actual Result	Pass/Fail
Normal State	25°C/50%	20°C~30°C/ 40%~60%	Data displayed normally, no alarm	25.2°C/51%, no alarm	Yes
Low Temperature + High Humidity	18°C/65%	20°C~30°C / 40%~60%	Dual-parameter out of bounds, trigger alarm	17.8°C/66%, alarm	Yes
High Temperature + Low Humidity	35°C/30%	20°C~30°C / 40%~60%	Dual-parameter out of bounds, trigger alarm	34.9°C/29%, alarm	Yes
Boundary Value Verification	28°C/55%	20°C~30°C / 40%~60%	Data displayed normally, no alarm	28.1°C/55.5%, no alarm	Yes
Humidity Critical Alarm	22°C/38%	20°C~30°C / 40%~60%	Humidity out of bounds, trigger alarm	21.9°C/37%, alarm	Yes
Sensor Fault Detection	Disconnected	-	"Device offline" prompt	Alarm triggered, abnormality prompted	Yes

4.2 Smoke Monitoring Function Testing

When testing the functionality of the smoke sensor, different concentrations of smoke environments were first artificially created. Subsequently, the microcontroller read the smoke concentration data detected by the sensor and transmitted it in real time to the WeChat mini-program. Managers could log in to the mini-program to view the current smoke concentration. To test the alarm function, a smoke concentration threshold was pre-set in the system. Once the concentration exceeded the set threshold, the buzzer's ability to emit an alarm was observed to ensure the normal operation of the alarm mechanism.

4.3 Clothing Fill Level Monitoring Function Testing

To test the clothing fill level monitoring function of the recycling bin, clothing of different heights was stacked inside the bin to simulate various fill states. The microcontroller read the distance data measured by the HC-SR04 sensor, converted it into fill level data, and uploaded it to the WeChat mini-program. Managers could open the mini-program to view the remaining volume inside the bin. A fill level threshold was pre-set, and when the monitored remaining volume was less than the set threshold, the buzzer's ability to emit an alarm was observed to ensure the normal operation of the alarm mechanism.

4.4 Weight Function Testing

When testing the weight monitoring function of the recycling bin, clothing of different weights was placed inside the bin to simulate actual recycling loads. The microcontroller read the weight data measured by the HX711 sensor and transmitted the information to the WeChat mini-program. Managers could open the mini-program to view the real-time weight of the clothing inside the bin. A weight threshold was pre-set in the system, and once the weight of the clothing inside the bin exceeded the threshold, the buzzer's ability to promptly emit an alarm was observed to test the reliability of the alarm function. The system accurately measures the weight of the clothing and promptly triggers alarms when the weight exceeds the set threshold.

4.5 Sprinkler Fire Extinguishing Function Testing

To test the operational performance of the water pump sprinkler fire extinguishing module, the administrator manually turned on the water pump sprinkler fire extinguishing switch and observed whether the module could immediately start working and perform sprinkler fire extinguishing inside the bin.

4.6 Test Summary

Based on the above tests, it can be concluded that when the environment exceeds the set thresholds, the used clothing recycling monitoring and management system can receive abnormal data and transmit it to the WeChat mini-program, while the buzzer triggers alarms. When the administrator manually operates the sprinkler fire extinguishing module switch, the water pump initiates sprinkler fire extinguishing settings.

5. Conclusion

With the rapid development of the e-commerce and fast fashion industries, the issues of used clothing overstock and inefficient recycling have become increasingly severe. Traditional recycling models suffer from coarse management, often resulting in situations where recycling bins overflow without timely processing and pose significant stacking hazards. To address these challenges, this study developed an intelligent monitoring and management system based on the STM32 microcontroller. By integrating temperature and humidity, smoke, ultrasonic, and weight sensors, the system monitors the status of recycling bins in real time and synchronizes the data to the WeChat mini-program via Wi-Fi, enabling remote monitoring and abnormal alerts.

The system development focuses on three core aspects: In terms of hardware, the low-power, high-performance STM32 is selected as the main controller, and sensors are carefully chosen after weighing cost and performance to ensure stable operation. The software adopts a layered modular architecture to enhance scalability and maintainability. For interaction design, the WeChat mini-program serves as the carrier, lowering the operational threshold. Practical tests demonstrate that the system can accurately collect data and trigger timely alarms, facilitating a shift from passive response to active regulation in recycling management, significantly improving efficiency and reducing risks.

Looking ahead, integrating image recognition for automatic used clothing classification or employing blockchain technology to establish a traceability system could further enhance the system's intelligence and process transparency. With its advantages of low cost, low power consumption, and ease of promotion, this solution provides a practical technical pathway for the standardized development and environmental efficiency improvement of the used clothing recycling industry.

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