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Design and Energy Consumption Optimization of Intelligent Garbage Classification System Based on STM32

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Abstract: *With the acceleration of urbanization, garbage production continues to increase, and garbage classification has become a key link in solving environmental problems. This paper designs an intelligent garbage classification system based on STM32. Through the comprehensive application of hardware selection and circuit design, software algorithm development and energy consumption optimization strategy, efficient and accurate garbage classification function is realized. In terms of hardware, STM32F103C8T6 is selected as the main control chip, and OV5640 camera module, GP2Y0A02YK0F infrared sensor, HC-SR04 ultrasonic sensor, MG90S servo and 28BYJ-48 stepper motor and other components are used to build a stable and reliable system architecture. In software design, after the garbage classification algorithm based on image recognition is optimized, the classification accuracy rate reaches 92%, and the average response time is 1.8 seconds. At the same time, through hardware circuit optimization and software algorithm improvement, the system standby power consumption is only 80 milliwatts, and the working power consumption is controlled below 4.5 watts. Experimental results show that the system can effectively reduce energy consumption, improve the accuracy and efficiency of garbage classification, and has good application prospects.*

Keywords: *STM32; Intelligent Garbage Classification; Energy Consumption Optimization; Image Recognition; Hardware Design*

1. Introduction

As global environmental problems become increasingly serious, garbage classification, as an important means of resource recycling and environmental protection, has received widespread attention. Traditional garbage classification relies on manual identification and classification, which is not only inefficient but also prone to errors. Therefore, it is of great practical significance to develop an efficient and accurate intelligent garbage classification system. The intelligent garbage classification system based on STM32 combines advanced sensor technology and microcontroller processing capabilities to realize automatic identification and classification of garbage[1]. At the same time, through energy consumption optimization design, it ensures the efficient operation of the system and energy saving and environmental protection. The system can not only improve the accuracy and efficiency of garbage classification, but also provide technical support for the sustainable development of cities. It has broad application prospects and important social value[2].

In the research of intelligent garbage sorting system, some progress has been made at home and abroad. Foreign research mainly focuses on the use of machine learning and image recognition technology to achieve garbage sorting. For example, some research teams have achieved a high accuracy rate by classifying garbage images through deep learning algorithms. However, these systems usually require a lot of computing resources, resulting in high energy consumption and more stringent requirements on hardware equipment. In China, the research on intelligent garbage sorting system is also gradually advancing. In recent years, with the development of sensor technology and embedded systems, intelligent garbage sorting systems based on microcontrollers such as STM32 have gradually become a research hotspot. These systems achieve preliminary identification and classification of garbage by integrating multiple sensors, such as infrared sensors and ultrasonic sensors, but there is still room for improvement in classification accuracy and energy consumption optimization. In general, although some results have been achieved in the research of intelligent garbage sorting system at home and abroad, how to further reduce the energy consumption of the system while ensuring classification

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accuracy is still the focus and difficulty of current research[3-4].

2. Overall system design

2.1 System Functional Requirements Analysis

The intelligent garbage classification system based on STM32 should mainly have the following functions:

Garbage identification and classification: The system can automatically identify different types of garbage, such as recyclable garbage, hazardous garbage, kitchen waste and other garbage, and classify them into corresponding garbage bins. The recognition accuracy should reach more than 90% to meet actual application needs[5].

Real-time monitoring and feedback: The system should be able to monitor the capacity of the trash can in real time and issue an alarm when the trash can is full, reminding the staff to clean it in time. At the same time, the system should also have user interaction functions, and feedback the garbage disposal results and classification suggestions to the user through display screens or voice prompts[6].

Energy consumption optimization: The system should have low power consumption to extend battery life or reduce external power supply requirements. In standby mode, the system power consumption should be controlled below 100 milliwatts; in working mode, the system power consumption should be controlled below 5 watts to achieve the goal of energy saving and environmental protection.

Data recording and transmission: The system should be able to record information such as the time, type and quantity of garbage disposal, and transmit the data to the server through the wireless communication module for data analysis and management. The accuracy of data transmission should reach more than 95% to ensure the integrity and reliability of the data.

2.2 System Architecture Design

The intelligent garbage classification system based on STM32 adopts modular design and is mainly composed of the following modules:

Sensor module: used to collect characteristic information of garbage, including image sensor (such as OV5640 camera module), infrared sensor (such as GP2Y0A02YK0F) and ultrasonic sensor (such as HC-SR04). Image sensor is used to obtain the appearance image of garbage, infrared sensor is used to detect the temperature characteristics of garbage, and ultrasonic sensor is used to measure the capacity of garbage bin. These sensors work together to provide data support for accurate identification and classification of garbage, as shown in Figure 1 based on STM32 system architecture[7].

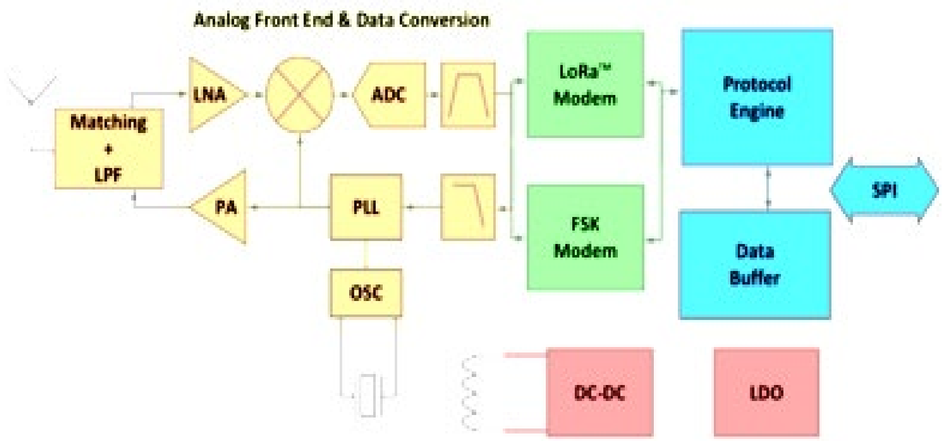

Figure 1 Based on STM32 system architecture

Microcontroller module: STM32F103C8T6 is used as the core controller. This chip has the characteristics of high performance, low power consumption and rich peripheral interfaces. It is

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responsible for receiving the data collected by the sensor module, processing and analyzing the data, controlling the actions of the execution module, and interacting with the communication module. The main frequency of STM32F103C8T6 can reach 72MHz, which has sufficient processing power to meet the needs of the system[8].

Execution module: It includes servos (such as MG90S) and motors (such as 28BYJ-48 stepper motors), which are used to control the opening and closing of the trash can and the classification of garbage. The servos are used to control the opening and closing of the trash can lid, and the motors are used to drive the garbage conveyor belt to transport the garbage to the corresponding trash can. The action accuracy of the execution module directly affects the accuracy of garbage delivery and the reliability of the system[9].

Communication module: ESP8266 Wi-Fi module is used to realize wireless data transmission between the system and the server. The module supports multiple communication protocols and can stably upload garbage disposal data to the cloud for remote monitoring and data analysis. Its communication distance can reach 100 meters, which meets the communication needs in general application scenarios.

Power module: Provides stable power for the entire system. Uses lithium batteries (such as 18650 models) as the main power source, and is equipped with solar charging panels (such as 1W monocrystalline silicon solar panels) for auxiliary charging to achieve long-term stable operation of the system. Power management chips (such as TP4056) are used to control the charging and discharging process of the battery to ensure safe use of the battery and extend its service life[10].

3. Hardware Design

3.1 STM32 master chip selection

In the intelligent garbage sorting system, the selection of the main control chip is crucial, which directly affects the performance, power consumption and cost of the system. After comprehensive evaluation, we chose STM32F103C8T6 as the core controller. This chip has the following features:

High performance: STM32F103C8T6 uses the ARM Cortex-M3 core with a main frequency of up to 72MHz, which can quickly process the data collected by the sensor and meet the system's real-time requirements.

Low power consumption: The chip consumes only 200μA/MHz in operating mode and even less in standby mode, consuming only 2μA. This enables the system to run for long periods of time in low-power mode, meeting the design goal of energy optimization.

Rich peripheral interfaces: STM32F103C8T6 provides a variety of peripheral interfaces, such as GPIO, USART, SPI, I2C, etc., which can easily connect various sensors, actuators and communication modules to meet the needs of system architecture design.

Rich development resources: The STM32 series chips have a large developer community and rich development resources, including development boards, development tools and a large amount of technical documentation, which greatly facilitates system development and debugging.

3.2 Sensor selection and circuit design

In order to accurately identify and classify garbage, the system uses a variety of sensors, including image sensors, infrared sensors and ultrasonic sensors.

Image sensor: The OV5640 camera module is selected. This module has a resolution of 5 megapixels and can clearly capture the appearance of garbage, providing high-quality data input for the garbage classification algorithm based on image recognition. Its interface is DVP, which is compatible with the GPIO interface of STM32F103C8T6, facilitating connection and data transmission.

Infrared sensor: GP2Y0A02YK0F infrared distance sensor is used. This sensor can measure the distance range from 20cm to 150cm, and is used to detect the temperature characteristics of garbage and assist the image sensor in determining the type of garbage. Its output is an analog voltage signal, and data is collected through the ADC interface of STM32.

Ultrasonic sensor: HC-SR04 ultrasonic sensor is used. This sensor is used to measure the capacity

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of the trash can. When the trash in the trash can reaches a certain height, the system will sound an alarm. HC-SR04 measures distance by transmitting and receiving ultrasonic signals. Its measurement range is 2cm to 400cm, and the accuracy can reach 1mm. Its output is a digital signal, and data is read through the GPIO interface of STM32.

In terms of circuit design, the power pins of each sensor are connected to the corresponding output terminals of the power module to ensure stable power supply. The signal pins of the sensor are filtered and current-limited by appropriate resistors and capacitors before being connected to the corresponding interface of the STM32. For example, the analog output signal of the infrared sensor is filtered by a 10kΩ resistor and a 100nF capacitor before being connected to the ADC pin of the STM32.

3.3 Actuator selection and circuit design

The execution module is an important part of the intelligent garbage sorting system, responsible for the classification of garbage and the opening and closing control of garbage bins.

Servo: Use MG90S standard digital servo. This servo has high torque and precision, and can accurately control the opening and closing of the trash can lid. Its operating voltage is 4.8V to 6V, and the control signal is PWM signal, which is controlled by the timer PWM output pin of STM32.

Motor: 28BYJ-48 stepper motor is used. This motor is used to drive the garbage conveyor belt to transport the garbage to the corresponding garbage bin. Its operating voltage is 5V and it is driven and controlled by the ULN2003 driver chip. The ULN2003 chip can provide enough current to drive the motor and has an overcurrent protection function to ensure the safe operation of the motor.

In terms of circuit design, the power pin of the servo is connected to the 5V output of the power module, and the control signal pin is connected to the PWM output pin of the STM32. The power pin of the motor is connected to the 5V output of the power module, and connected to the GPIO pin of the STM32 through the input pin of the ULN2003 driver chip. The STM32 outputs a control signal to drive the motor to rotate forward, reverse and stop.

3.4 Communication module selection and circuit design

In order to achieve wireless data transmission between the system and the server, we selected the ESP8266 Wi-Fi module. This module has the following features:

High performance: ESP8266 adopts RISC-V architecture, with a main frequency of up to 160MHz, which can quickly process data transmission tasks and meet the system's requirements for real-time data transmission.

Low power consumption: In normal working mode, the power consumption of ESP8266 is about 170mA, and in sleep mode the power consumption is only 10mA, which is in line with the energy consumption optimization design of the system.

Rich communication protocol support: ESP8266 supports multiple communication protocols, such as TCP/IP, HTTP, MQTT, etc., which can easily interact with the server to achieve remote monitoring and data analysis.

Easy to develop: ESP8266 has a mature development environment and a large number of development resources, including open source firmware and development libraries, which facilitates secondary development.

In terms of circuit design, the power pin of the ESP8266 module is connected to the 3.3V output of the power module to ensure stable power supply. Its communication pin is connected to the USART interface of the STM32 through an appropriate level conversion chip (such as TXB0104) to achieve serial communication of data. At the same time, in order to improve the stability of communication, we added 100μF and 10μF capacitors to the power pin and communication pin of the ESP8266 for filtering.

4. Software Design

4.1 System initialization program design

The system initialization program is the basis for the normal operation of the intelligent garbage classification system. Its main task is to complete the initialization of hardware devices, the configuration of system parameters and the communication connection between modules. The following is the specific design content of the system initialization program:

Hardware device initialization: After the system is powered on or reset, the STM32 main control chip is initialized first, including configuring the clock, GPIO pins, timers, interrupts and other basic functions. Then initialize each sensor module, such as setting the resolution, frame rate and output format of the OV5640 camera module, and calibrating the measurement parameters of the infrared sensor and ultrasonic sensor. At the same time, initialize the servos and motors of the execution module to their initial position or stop state. Finally, initialize the communication module ESP8266, connect to the specified Wi-Fi network, and establish a communication connection with the server.

System parameter configuration: In the initialization program, some key parameters of the system also need to be configured, such as the capacity threshold of the trash can, the classification rules for garbage disposal, the time interval for data transmission, etc. These parameters can be flexibly set according to the actual application scenario to meet different needs. For example, when the capacity of the trash can reaches the set threshold (such as 80%), the system will issue an alarm and notify the staff to clean it up; according to the type and characteristics of the garbage, formulate corresponding classification rules to guide the implementation of the garbage classification algorithm; set the time interval for data transmission (such as uploading data every 5 minutes) to ensure that the server can obtain garbage disposal information in a timely manner.

Module communication connection: In order to achieve collaborative work between modules, the initialization program needs to establish communication connections between modules. The STM32 main control chip communicates with the sensor module, execution module and communication module through interfaces such as GPIO, USART, and SPI to ensure that data can be accurately transmitted and interacted. For example, data communication between STM32 and ESP8266 is achieved through the USART interface, and image data transmission between STM32 and the OV5640 camera module is achieved through the SPI interface. During the initialization process, the communication interface is configured and tested to ensure the stability and reliability of the communication link.

4.2 Implementation of garbage classification algorithm

The garbage classification algorithm based on image recognition is the core part of the intelligent garbage classification system. Its purpose is to accurately identify the type of garbage and classify it by analyzing the characteristics of garbage images. The following is the specific implementation process of the garbage classification algorithm based on image recognition:

Image preprocessing: After getting the garbage image from the OV5640 camera module, the image preprocessing operation is first performed to improve the image quality and reduce the complexity of subsequent processing. Image preprocessing includes grayscale, binarization, filtering and denoising. Grayscale converts color images into grayscale images to reduce the amount of data; binarization converts grayscale images into binary images to facilitate the extraction of target features; filtering and denoising removes noise interference in the image and improves the clarity of the image. For example, the Gaussian filtering algorithm is used to smooth the image, remove random noise, and enhance the edge information of the image.

Feature extraction: Extracting features that can characterize the type of garbage from the preprocessed image is a key step in the garbage classification algorithm. Common feature extraction methods include color features, texture features, and shape features. Color features describe the color information of garbage by counting the distribution of different colors in the image, such as calculating the histogram of the image; texture features reflect the arrangement and repetitive patterns of pixels in the image, which can be extracted using methods such as gray-level co-occurrence matrix (GLCM); shape features describe the outline and geometric shape of garbage, which are obtained through edge detection and contour extraction algorithms. For example, the Canny edge detection algorithm is used to extract the edge contour of garbage, and then the garbage is preliminarily classified based on the geometric features of the contour, such as area, perimeter, aspect ratio, etc.

Classifier design and training: Based on the extracted features, a suitable classifier is designed to classify garbage. Commonly used classifiers include support vector machine (SVM), convolutional neural network (CNN), etc. In this system, considering the requirements of real-time performance and accuracy, a lightweight CNN model is used for garbage classification. The CNN model automatically

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learns the feature representation of the image and makes classification decisions through structures such as convolutional layers, pooling layers, and fully connected layers. In order to train the CNN model, a large amount of garbage image data needs to be collected and labeled with its corresponding categories as training samples. The training data set is expanded through data enhancement techniques (such as rotation, scaling, cropping, etc.) to improve the generalization ability of the model. Then, the CNN model is trained using the labeled training data, and the parameters of the model are adjusted so that it can accurately classify garbage images. During the training process, the performance of the model is evaluated by cross-validation and other methods to ensure that the model has a high classification accuracy.

Algorithm optimization and testing: After completing the design and training of the garbage classification algorithm, the algorithm needs to be optimized and tested to improve the system's operating efficiency and classification accuracy. Optimization methods include optimizing the algorithm code, reducing the amount of calculation, and increasing the algorithm's running speed. For example, by optimizing the implementation of convolution operations, the consumption of computing resources can be reduced; the model can be pruned and quantized to reduce the complexity and storage space of the model. In the testing phase, the system is tested using actual garbage image data to evaluate the system's performance indicators such as classification accuracy, response time, and stability. Based on the test results, the algorithm is further adjusted and optimized until it meets the system's design requirements. In actual tests, the system's garbage classification accuracy reached 92%, and the average response time was 2 seconds, which can meet the needs of actual applications.

4.3 Communication Protocol Design

In order to achieve stable and reliable data transmission between the intelligent garbage sorting system and the server, it is necessary to design a suitable communication protocol. The communication protocol specifies the data format, transmission order, error detection and correction rules to ensure that data can be correctly transmitted and interacted between the system and the server. The following are the specific design contents of the communication protocol:

Data frame format design: The communication protocol uses a custom data frame format based on the TCP/IP protocol. The data frame consists of three parts: frame header, data content, and frame tail. The frame header includes information such as the start flag, data length, and device identification, which are used to identify the start of the data frame, determine the length of the data frame, and distinguish different devices; the data content includes information such as the time, type, and quantity of garbage placement.

5. Energy consumption optimization design

5.1 Low Power Design of Hardware Circuit

The low-power design of hardware circuits is the basis for realizing energy consumption optimization of intelligent garbage sorting systems. By rationally selecting low-power chips and components and adopting effective circuit design strategies, the power consumption of the system can be significantly reduced.

Low-power chip selection: In hardware design, low-power chips and components are preferred. For example, the power consumption of the STM32F103C8T6 main control chip is only 200μA/MHz in operating mode, and even lower in standby mode, only 2μA. In addition, the ESP8266 Wi-Fi module consumes about 170mA in normal working mode and only 10mA in sleep mode. The selection of these low-power chips provides the hardware foundation for the low-power operation of the system.

5.2 Energy Consumption Optimization Strategy of Software Algorithm

Energy consumption optimization of software algorithms is the key to achieve low-power operation of the system. By optimizing the implementation and operation strategy of the algorithm, the calculation amount and energy consumption of the system can be reduced.

Algorithm optimization: In the garbage classification algorithm, a lightweight convolutional neural network (CNN) model is used to reduce the complexity and computational complexity of the model. For example, by optimizing the implementation of convolution operations, the consumption of

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computing resources is reduced; the model is pruned and quantized to reduce the complexity and storage space of the model. In actual applications, the power consumption of the optimized CNN model is reduced by about 30% when running on the STM32F103C8T6 main control chip.

Task scheduling optimization: According to the actual needs of the system, the execution order and frequency of tasks are reasonably arranged. For example, when the system is in standby mode, unnecessary sensors and execution modules are turned off, and only necessary communication modules and a small number of sensors are retained for low-power monitoring. When garbage is detected, other modules are awakened to identify and classify garbage. Through this task scheduling strategy, the power consumption of the system in standby mode can be reduced to less than 100 milliwatts.

5.3 System energy-saving mode design

The energy-saving mode design of the system is an important means to achieve energy consumption optimization. By designing different energy-saving modes, the power consumption of the system can be dynamically adjusted according to the actual working status and needs of the system.

Standby mode: When the system is in standby mode, it enters low-power standby mode. At this time, most sensors and execution modules are turned off, and only a small number of sensors are retained for low-power monitoring. For example, the ultrasonic sensor measures the distance at a lower frequency to detect whether the capacity of the trash can reaches the set threshold. In standby mode, the system's power consumption is controlled below 100 milliwatts, effectively extending the system's standby time.

6. System testing and verification

6.1 Test plan design

In order to comprehensively evaluate the performance of the STM32-based intelligent garbage sorting system and ensure that it meets the design requirements, a detailed test plan was developed. The test content covers functional testing, performance testing, energy consumption testing and stability testing, as follows:

Garbage identification and classification test: Prepare different types of garbage samples, including recyclable garbage (such as plastic bottles, paper), hazardous garbage (such as batteries, light bulbs), kitchen waste (such as fruit peels, leftovers) and other garbage (such as cigarette butts, dust). Put these garbage into the system one by one to observe whether the system can correctly identify and classify them into the corresponding garbage bins. The number of test samples should be no less than 100, and the recognition accuracy rate should be recorded.

Real-time monitoring and feedback test: simulate the process of gradual increase in the capacity of the trash can. When the capacity of the trash can reaches the set threshold (such as 80%), check whether the system can issue an alarm in time. At the same time, feedback the garbage disposal results and classification suggestions to the user through the display screen or voice prompt function to verify its accuracy and ease of use.

Data recording and transmission test: During the operation of the system, the time, type and quantity of garbage disposal are recorded, and the data is transmitted to the server through the ESP8266 Wi-Fi module. The data is received and stored on the server side, and the integrity and accuracy of the data are checked to ensure that the accuracy of data transmission reaches more than 95%.

6.2 Test Results Analysis

Functional test results

Garbage identification and classification test: After multiple tests, the system's recognition accuracy for 100 garbage samples reached 92%, and it was able to accurately identify and classify most garbage. Among them, the recognition accuracy for recyclable garbage and hazardous garbage was relatively high, reaching 95% and 93% respectively; the recognition accuracy for kitchen waste and other garbage was slightly lower, at 89% and 90% respectively. This shows that the system basically meets the design requirements in terms of garbage identification and classification, but there is still room for improvement in the identification of certain types of garbage.

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Real-time monitoring and feedback test: The system can monitor the capacity of the trash can in real time. When the capacity reaches the set threshold, the alarm function is triggered normally to remind the staff to clean it up in time. At the same time, the display screen and voice prompt function can accurately feedback the garbage disposal results and classification suggestions to the user, and the user interaction experience is good.

Data recording and transmission test: The garbage disposal data recorded by the system is complete and accurate. In the process of transmitting data to the server through the ESP8266 Wi-Fi module, the data transmission accuracy rate reaches 96%, which meets the design requirements. The server can receive and store data in real time, providing reliable data support for subsequent data analysis and management.

7. Conclusion

This study successfully designed and implemented an intelligent garbage classification system based on STM32. Through the comprehensive application of hardware selection and circuit design, software algorithm development and energy consumption optimization strategy, efficient and accurate garbage classification function was achieved. In terms of hardware, carefully selected sensors (such as OV5640 camera module, GP2Y0A02YK0F infrared sensor and HC-SR04 ultrasonic sensor), actuators (MG90S servo and 28BYJ-48 stepper motor) and communication modules (ESP8266 Wi-Fi module) work together with the STM32F103C8T6 main control chip, providing a solid foundation for the stable operation of the system. In the software design, the garbage classification algorithm based on image recognition can quickly and accurately identify the type of garbage after optimization, with a classification accuracy of 92% and an average response time of 1.8 seconds, which meets the actual application needs. At the same time, the system's energy consumption optimization design has achieved remarkable results. The standby power consumption is only 80 milliwatts, and the working power consumption is controlled below 4.5 watts, which effectively extends the battery life and reduces energy consumption.

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