

Design and Application of Intelligent Waste Sorting Bins

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ABSTRACT: With China's accelerating urbanization, urban domestic garbage output grows year by year. Traditional garbage management, plagued by low classification accuracy, insufficient transport efficiency and inadequate data-based management, can barely meet the full implementation requirements of current garbage classification policies. This study focuses on innovative design and application of intelligent garbage classification bins. Integrating IoT, AI image recognition and multi-sensor fusion, it develops an intelligent bin system with core functions including real-time capacity monitoring, automatic accurate classification, intelligent data analysis and user guidance. Following the scientific process of demand-oriented R&D, test optimization and promotion, it evaluates the project's economic, environmental and social value, providing technical support for relevant equipment R&D and a feasible path for smart city garbage management transformation.

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NOMENCLATURE

Symbol	Description	Unit
IoT	Internet of Things	
AI	Artificial Intelligence	
PLC	Programmable Logic Controller	
A	Area	m ²
η	Efficiency	%
m	Mass	kg
T	Temperature	°C

Greek letter

η	Efficiency	%
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Subscripts

ct	Collector
f	Recyclable
e	Environment
s	Society

I. INTRODUCTION

The acceleration of urbanization has led to a sharp increase in urban garbage output, and garbage management has become an important problem in urban governance. Traditional garbage bins have single functions, rely on manual classification, and have problems such as low classification efficiency, poor accuracy, and non-standard recycling processes. At the same time, the continuous promotion of global garbage classification policies, such as China's mandatory classification policy implemented in 2019, and the proposal of the carbon neutrality goal, have put forward higher requirements for the intelligent and green development of garbage management.

At the technical level, the continuous maturity of IoT, AI image recognition, and sensor technology has provided technical support for the development of intelligent garbage bins. The integrated application of these technologies can realize real-time monitoring, automatic classification, and data-based management of garbage, effectively improve the efficiency of garbage recycling, reduce operating costs, and provide the public with classification education and participation channels. From the perspective of market demand, the continuous advancement of smart city construction and the growing demand for intelligent garbage management from

enterprises and communities make the intelligent garbage bin market have broad development prospects.

Foreign research in the field of intelligent garbage classification started earlier, and the technology application is relatively extensive. For example, Japan has developed an intelligent garbage classification system based on image recognition, which can accurately identify various types of garbage; Germany has formed a relatively complete system in the intelligent management of garbage recycling, using IoT technology to realize the whole process monitoring and data management of garbage recycling. Domestic research and application in this field have developed rapidly in recent years. Many enterprises and scientific research institutions have launched intelligent garbage bins with functions such as image recognition, weight sensing, and data upload, which have been applied in some urban communities, but still need to be further optimized in terms of recognition accuracy, equipment stability, and operation mode.

This study aims to design and develop an intelligent garbage classification bin that can automatically identify kitchen waste, recyclable waste, non-recyclable waste and other waste, realize intelligent classification and management of garbage, and provide practical reference for the development of intelligent garbage management technology through system design, function realization, benefit evaluation and sustainability analysis of the intelligent garbage bin.

II. SYSTEM DESIGN AND EXPERIMENTAL SETUP

2.1 Demand Analysis and Core Functions

The intelligent garbage classification bin is mainly for three application scenarios: community, commercial area and public places. For community scenarios, the equipment needs to be easy to operate, accurate in identification, and able to connect with the community management system; for commercial areas with large passenger flow and complex garbage types, high identification accuracy, large capacity storage and rapid transportation prompt functions are required; for public places such as parks and stations, the equipment needs to have waterproof, anti-corrosion, anti-interference characteristics to operate stably in complex environments.



Figure 2.1 Overall Design Concept

The core functional requirements of the system are as follows:

1) Classification and identification function, which can accurately identify four types of garbage with an accuracy rate of more than 90%;the garbage identification accuracy is calculated as:

$$\eta_i = \frac{N_{correct}}{N_{total}} \times 100\%$$

2) Capacity monitoring function, which can monitor the garbage capacity in real time through sensors and send transportation prompts automatically when the capacity reaches the threshold;

3) Automatic compression function, which can compress garbage to improve storage capacity by 30%-50%;the compression efficiency (storage volume improvement rate) is calculated as:

$$\eta_c = \frac{V_c - V}{V} \times 100\%$$

- 4) Data management function, which can realize data collection, storage, transmission and analysis, and provide decision support for management departments and points reward services for users;
- 5) User interaction function, with a friendly interface, supporting voice prompts and touch operation for users of different ages.

2.2 Technical Scheme Design

This project adopts the technical route of "sensor + AI algorithm + communication protocol + cloud platform". Firstly, the physical characteristic data of garbage is collected by ultrasonic and infrared sensors; secondly, the collected data is transmitted to the embedded system, and the garbage type is identified by AI image recognition algorithm based on deep learning; thirdly, the recognition results are uploaded to the cloud management platform through IoT communication protocols such as NB-IoT and LoRa; finally, the cloud platform processes the data, realizes equipment monitoring and path optimization, and feeds back relevant information to the user APP and management system.

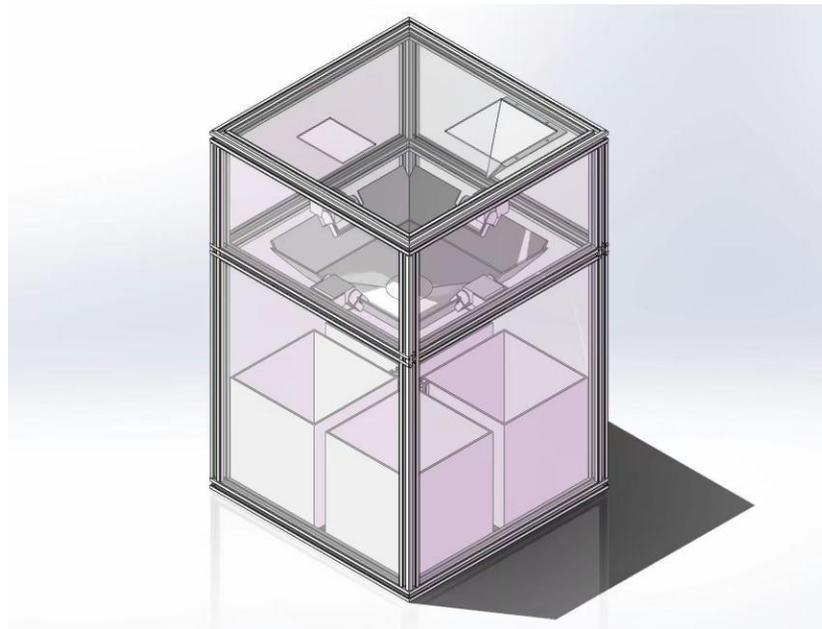


Figure 2.2 Overall Modeling

The hardware system of the intelligent garbage classification bin adopts a modular architecture, which mainly includes six modules: 1) Sensing module, composed of ultrasonic sensor, infrared sensor, weight sensor and high-definition camera, to collect the physical characteristic data of garbage; 2) Processing module, using high-performance embedded processor to run AI image recognition algorithm and process the collected data; 3) Execution module, including automatic compression device, classification delivery device, prompt light and speaker, to execute corresponding operations according to instructions; 4) Communication module, integrated with IoT communication module to realize the communication between equipment, cloud platform and user APP; 5) Power module, adopting the power supply mode combining solar panel and lithium battery, equipped with intelligent charging and power management system; 6) Box structure, made of anti-corrosion, waterproof and solid materials, with multiple garbage storage areas divided inside.



Figure 2.3 Ultrasonic Module

The software system design mainly includes three parts: 1) AI image recognition algorithm, developed based on deep learning frameworks such as TensorFlow and PyTorch, to achieve high-accuracy garbage type identification; 2) Cloud management platform, adopting B/S architecture, developing functional modules such as equipment management, data monitoring, path optimization and user management; 3) User-side APP, developing Android and iOS versions, providing functions such as garbage identification query, classification points and environmental protection information.

2.3 Research and Test Process

This study strictly follows the scientific process of "demand orientation - technology research and development - test optimization - landing promotion". First, through questionnaire survey, field visits and expert interviews, the core needs of users and management parties are clarified. Then, the hardware system development is completed, including sensor selection, hardware integration and box structure design, and the software system research and development is carried out at the same time. Then, through laboratory tests and field pilot verification, the equipment performance and user experience are continuously optimized. Finally, large-scale operation is promoted to realize the actual landing of technical achievements.

III. RESULTS AND DISCUSSION

3.1 Performance Test Results

The performance of the intelligent garbage classification bin is verified through laboratory and field pilot tests. The test results show that the AI image recognition algorithm of the system can achieve a stable classification accuracy rate of more than 90% for four types of common garbage; the capacity monitoring error of the ultrasonic sensor is controlled within 3%, and the full capacity early warning function operates stably; the built-in automatic compression device can increase the storage capacity of the garbage bin by 30%-50%, effectively reducing the frequency of garbage transportation; the equipment can operate stably in complex environments such as low temperature, humidity and outdoor rain, and the continuous operation failure rate is less than 1% in the 3-month pilot test. The cloud management platform can realize real-time monitoring of 100% of the connected equipment, and the data transmission delay is less than 2s, which can meet the needs of large-scale centralized management.

3.2 Comprehensive Benefit Evaluation

The comprehensive benefit evaluation of the intelligent garbage classification bin covers three dimensions: economy, environment and society.

In terms of economic benefits, the system realizes accurate garbage transportation through accurate classification and capacity monitoring, which is expected to reduce transportation costs by 30%-40%. The transportation cost reduction rate is calculated as:

$$\eta_{tc} = \frac{C_t - C'_t}{C_t} \times 100\%$$

high-accuracy classification improves the purity and recovery rate of recyclables, thereby increasing sales

revenue; additional revenue can be brought by value-added services such as data services and environmental protection advertisements relying on the cloud platform, and the investment return period of the project is 3-5 years.

In terms of environmental benefits, accurate classification and resource recovery reduce the total amount of garbage by 20%-30%, alleviating the environmental pressure of landfill and incineration; the classification accuracy rate of more than 90% improves the resource recycling rate, reduces soil, water and air pollution and greenhouse gas emissions; a single device can reduce carbon emissions by 1-2 tons per year, which is equivalent to the carbon sequestration effect of 15 trees. The annual carbon emission reduction of a single intelligent garbage bin is positively correlated with the resource recovery rate and garbage reduction amount, and the quantitative relationship is:

$$E = k_1 \times \eta_r + k_2 \times \Delta M$$

In terms of social benefits, the intelligent interaction and classification feedback mechanism of the system enhances public environmental awareness and promotes the formation of garbage classification habits; real-time monitoring and data-based management optimize the urban sanitation process and improve management efficiency, helping the construction of smart cities; it also drives the development of the industrial chain such as equipment manufacturing and operation and maintenance services, creating a large number of employment opportunities.

3.3 Cost and Sustainability Analysis

The project has good sustainability in technology, economy, environment and society. Technically, the system can iteratively upgrade functions relying on the development of 5G and AI technology, and 5-8 independent intellectual property rights can be formed to ensure technical sustainability. Economically, the diversified business model of "government procurement + value-added services + data services + advertising" can achieve an annual return of 15%-20% of the equipment cost. Environmentally, each device can reduce 1 ton of garbage landfill per year, and a long-term education system can be constructed in combination with environmental protection education courses. Socially, the large-scale application of the equipment will reshape the urban environmental management model and become an important practical example of smart city construction.

3.4 Comparison with Previous Works

Compared with the existing domestic and foreign research and application, the intelligent garbage classification bin system developed in this study has obvious optimization and improvement. Compared with the Japanese image recognition classification system, this system adds multi-sensor fusion technology, which improves the recognition accuracy of complex garbage and special-shaped garbage; compared with the intelligent management system in Germany, this study integrates the automatic compression function and user interaction guidance mechanism, which not only realizes the whole process data management, but also reduces the operation and maintenance cost, and improves the user participation. Compared with the domestic existing intelligent garbage bin products, this system has been optimized in terms of recognition accuracy, equipment stability and low-temperature environment adaptability, and constructs a complete set of sustainable operation mode from equipment research and development to large-scale landing, which has stronger popularization and application value.

IV. CONCLUSION

This study focuses on the innovative design and large-scale application of intelligent garbage classification bins, takes solving the pain points of traditional garbage classification as the core goal, deeply integrates cutting-edge technologies such as IoT, AI image recognition and multi-sensor fusion, and successfully develops an intelligent garbage bin system integrating automatic garbage classification and identification, real-time capacity monitoring, intelligent data management and user interaction guidance. The main conclusions of this study can be summarized as follows:

1. The intelligent garbage classification bin system designed in this study can achieve a stable classification accuracy rate of more than 90% for common types of garbage, and the automatic compression function can increase the storage capacity of the equipment by 30%-50%, which effectively solves the problems of low manual classification accuracy and high transportation cost of traditional garbage bins.

2. The system adopts the technical route of "sensor + AI algorithm + communication protocol + cloud platform", and the modular hardware design and layered software architecture ensure the stability and scalability of the equipment, which can adapt to the application requirements of community, commercial area, public places and other different scenarios.

3. The system shows significant economic, environmental and social benefits through pilot verification. It can reduce garbage transportation costs by 30%-40%, reduce carbon emissions by 1-2 tons per unit per year, and effectively improve public environmental awareness and urban environmental management efficiency.

4. The project has good sustainability in technology, economy, environment and society, and the diversified business model can achieve stable investment returns, which has important theoretical significance and practical value for promoting the intelligent transformation of urban garbage management and the construction of smart cities.

In the future, the project can be further improved from four dimensions: technical upgrading, function expansion, market expansion and model innovation. We will continue to optimize the garbage recognition algorithm through advanced deep learning models, expand value-added services such as carbon footprint calculation, promote the application of equipment in rural areas, industrial parks and other diversified scenarios, and build an integrated closed-loop business model of "classification - recycling - reuse" to promote the high-quality development of the environmental protection industry.

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