Design of an Intelligent Waste Bin Based on Machine Vision Technology

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Abstract. This study focuses on the design of an intelligent waste bin based on machine vision technology. First, the research background, significance, and current status of domestic and international studies are analyzed to clarify the necessity of developing such a system. On this basis, the overall design of the intelligent waste bin is presented, including its structural composition, working principle, and hardware framework. The software design is then introduced in detail, covering the classification algorithm, program development, and system implementation process. The proposed system integrates camera modules and vision-based recognition algorithms to identify waste types and automatically guide waste into corresponding categories. Experimental results show that the system achieves a higher level of automation in classification and demonstrates stable performance under typical usage conditions. This research not only improves the intelligence and practicality of waste bins but also provides a feasible solution for promoting resource recycling and environmental sustainability. Furthermore, it offers useful reference for the wider application of machine vision technology in intelligent environmental management systems.

Keywords: Machine vision technology; Intelligent waste bin; Waste classification.

1. Introduction

1.1. Research Background and Significance

With the development of society and technology, people's lifestyles have undergone tremendous changes. Waste management has become a significant issue in modern urban life. Statistics show that the global annual production of domestic waste has reached tens of billions of tons, exerting immense pressure on the environment and posing threats to human health[1]. Therefore, how to effectively classify, collect, and process domestic waste has become an urgent problem to solve.

Machine vision technology, as an important branch of computer vision, has made remarkable progress in object recognition and image processing. This technology can automatically acquire, analyze, and understand image information, possessing strong data processing capabilities that can effectively enhance the intelligence level of waste bins[2]. An intelligent waste bin integrated with machine vision technology can not only improve the efficiency and accuracy of waste classification but also provide optimization suggestions for waste management through data analysis, thereby promoting the intelligent upgrading of waste management systems.

The purpose of this study is to design an intelligent waste bin based on advanced machine vision technology, aiming to accurately identify and classify different types of waste to promote effective recycling and reduce environmental pollution. The design and development of intelligent waste bins not only meet the needs of current environmental policies but also have significant implications for improving urban management levels and residents' quality of life.

Through in-depth research and practical exploration, this paper aims to provide theoretical support and technical solutions for the design and development of intelligent waste bins, promote the popularization of waste classification technology, and contribute to building a green, healthy, and sustainable urban environment. Additionally, this study will explore the challenges and solutions encountered in the practical application of intelligent waste bins, offering references for future research in related fields.

1.2. Current Status of Research at Home and Abroad

In recent years, intelligent waste bins, as a typical application of environmental governance combined with artificial intelligence, have attracted widespread attention from scholars both domestically and internationally.

In foreign countries, research in this area started earlier, with a focus on improving the accuracy of waste recognition and system operational efficiency. For example, countries such as Japan and Germany have already implemented automatic waste classification bins based on sensors and vision recognition, which have been deployed in communities and public places and achieve high classification accuracy[1]. Moreover, some studies have attempted to introduce deep learning algorithms to enhance the recognition capability for complex waste categories and even integrate with the Internet of Things (IoT) platform to enable real-time monitoring and remote management of waste disposal volume and recycling efficiency.

In China, driven by policies and technological advancements, research has started later but has made rapid progress. Most studies focus on waste classification methods based on image recognition, emphasizing the use of convolutional neural networks (CNN), transfer learning, and other algorithms to improve classification accuracy[3]. Additionally, many domestic studies have explored the integration of intelligent waste bins with IoT, voice interaction, and ergonomic design to achieve more user-friendly experiences and more efficient waste processing. Several universities and enterprises have developed prototypes, but there are still shortcomings in recognition speed, adaptability to complex environments, and cost control.

In summary, foreign research emphasizes the maturity of technology and actual deployment, while domestic research tends to focus on algorithm exploration and integration of multiple technologies. The future development trends mainly focus on three aspects: (1) further improving classification accuracy and real-time performance; (2) achieving low-cost, modular design to promote large-scale application; (3) combining IoT and big data analysis to expand the role of intelligent waste bins in smart cities.

2. Overall Design of the Intelligent Waste Bin

2.1. Overall Design Scheme of the Intelligent Waste Bin

Designed to meet the application scenarios mentioned before, the intelligent waste bin is aiming to combine the intelligent garbage classification and other functions by using the latest machine vision technology. It can automatically identify waste, automatically classify, sort and crush. It can save labor cost and increase classification work efficiency, ensuring that waste resources can be used again without any human control. The purpose of the intelligent garbage bin design is to improve the sorting work efficiency and sorting accuracy, reduce manual intervention, protect the environment and realize resource recycling.

The bin can integrate multi-sensors, such as cameras, infrared sensors, weight sensors, etc., and the sensor is used for a variety of waste type identification and classification by each sensor cooperates and works together. The bin also uses an efficient garbage compression device in order to increase the storage space capacity and reduce the total volume of garbage stored. The main functions and technical parameters of the intelligent waste bin system are as follows in **Table 1**:

Table 1. Functions and Technical Parameters of the Intelligent Waste Bin

Function	Description	Technical Parameters
Image Recognition	Captures waste images through the camera	Resolution: 1080p
Infrared Sensing	Detects the amount of waste in the bin	Sensing range: 50cm
Weight Measurement	Calculates the weight of waste	Accuracy: ±10g

On the software side, intelligent bin uses a special algorithm, which can process the image information shot by the camera, identify different kinds of garbage, such as recyclables, hazardous materials, wet garbage, dry trash, and perform sorting according to recognition results of the classification results. The algorithm will improve accuracy by processing the captured photo using noise reduction, feature extracting technologies to assist in identifying types of trash.

Meanwhile, the intelligent bin provides Internet service; it will report generated garbage data on a cloud server, then help managers or government departments make analysis reports through network connection so as to improve garbage classification efficiency[4]. By analyzing big data, it improves city management intelligence level and improves garbage collection operation ability. This further helps to implement environmental protection and promotes sustainable urbanization..

As described above, the overall design combines machine vision and automatic control, as well as multi-sensor technology fusion with cloud computing, thus helps to improve automated and intelligentized treatment for recycling resources from household kitchen, promoting garbage sorting. This integration effectively reduces the amount of garbage in bins and improves the convenience of the user, while decreasing stress on cities from managing waste.

2.2. Working Principle of the Intelligent Waste Bin

The intelligent waste bin mainly uses machine vision technology that combines the camera, image processor, and AI algorithm to determine the type of waste to classify and process. The system can automatically identify and classify various types of waste, such as recycling products, hazardous waste, wet waste, and dry waste. This makes waste sorting both faster and more accurate.

At the heart of this process is image recognition. First, a photograph is taken by the camera of what is in the garbage bin; then, it pre-processes the images through image processing algorithms—such as noise elimination, edge detection, contrast improvement — and feeds them into the deep learning algorithm for further analysis; finally, the system provides an answer to how the waste will be handled. Deep learning refers to a class of algorithms based on artificial neural networks. The deep learning model used here is usually convolutional neural network (CNN), which can be expressed by [5]:

$$y = f(Wx + b) \tag{1}$$

where x represents the input image data, W and b are the weight and bias parameters, respectively, f is the activation function, and y is the output result, representing the category of the waste.

After obtaining the category of the waste, the intelligent waste bin will perform the corresponding operation according to the preset program, such as opening a specific waste bin door to allow the waste to be placed in the correct category.In addition, the system can also connect to the Internet to upload waste processing data in real-time for monitoring and analysis by management personnel[6]. To more intuitively demonstrate the working principle of the intelligent waste bin, the **Fig. 1** illustrates its working process:

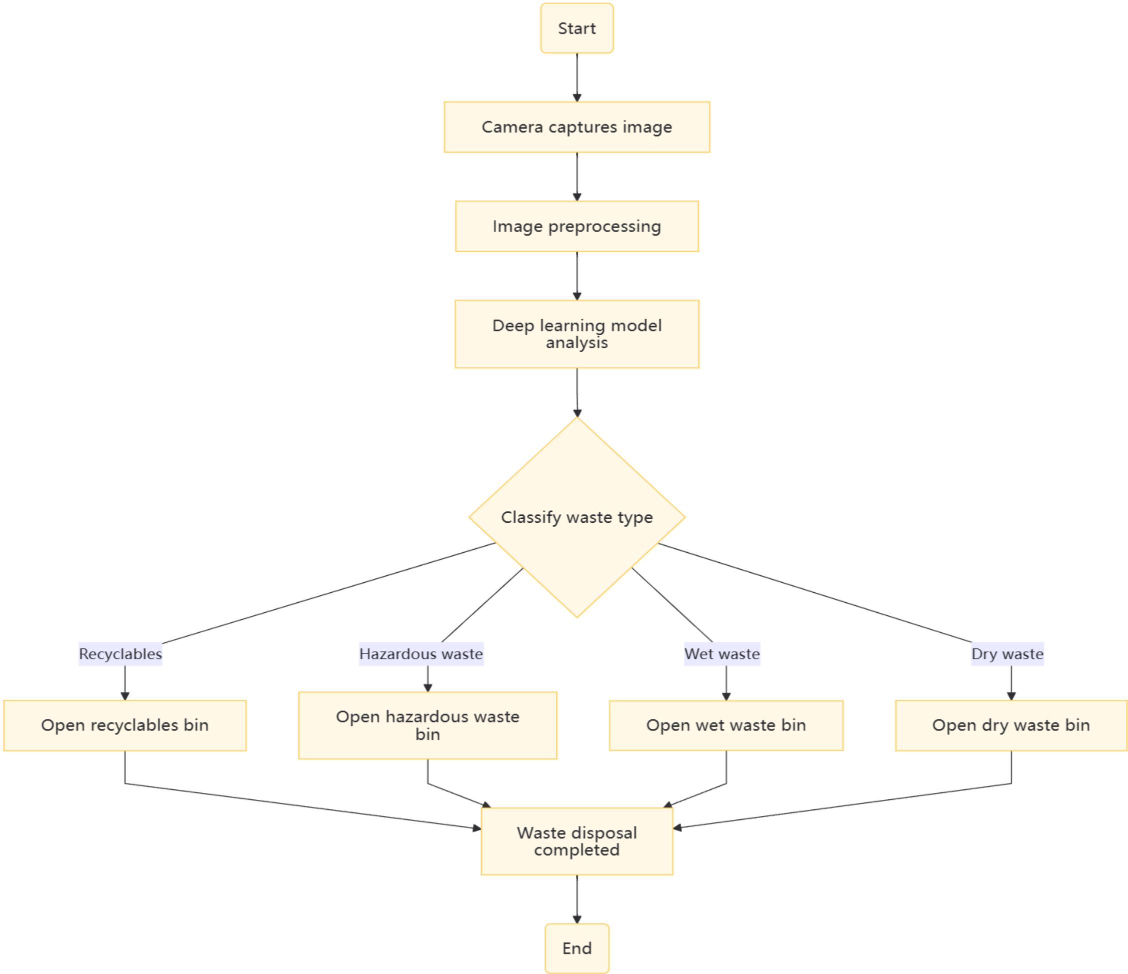

Fig. 1 Working process

As can be seen from the above Fig. 1, the intelligent waste bin automates and intelligences every step from capturing the image to completing the waste disposal, greatly improving the efficiency and accuracy of waste classification. Moreover, the intelligent design of the system also enables the waste bin to adapt to different usage environments, offering high flexibility and practicality[7].

2.3. Hardware Components of the Intelligent Waste Bin

The hardware of intelligent waste bin is the base of system, which consists of sensors, controllers, output devices and power supplies, to enable it to identify and complete the work of waste sorting and treatment. The sensor module mainly includes temperature sensors, pressure sensors, etc.

(1) Sensor Modules

Sensors work as the "sensing layer" of the bin. The infrared sensors are used to monitor whether the lid is open and if the garbage has been put in; the weight sensor monitors the amount of garbage inside the bin and reminds the cleaning workers when to come for clean-up; the camera serves as an image sensor to get pictures of the waste, and send it back to the controller [1].

(2) Control Unit

The control unit is the brain of the whole system, it adopts the STM32 microcontroller or Arduino microcontroller, its main functions are to control all data inputs provided by various sensors and machine vision algorithm processing results, realize the garbage classification and waste recognition, send instructions such as action signals to control the actuator (e.g., servo motor) with output actions such as sorting.

(3) Actuators

Actuators The mechanical components of the intelligent waste bins mainly refer to motors, servos and electric pushrods used to realize functions that complete specific mechanical operations by executing the control commands and the recognition results generated from the control unit. That is to say, they are able to automatically open the waste bin lid corresponding to the result of a particular recognition result to send the wastes into the right compartment of the intelligent waste bin in accordance with the designed purpose. More importantly, these actuators drive the compression device of the bin so as to compress the accumulated waste in the storage room into a small volume to enhance its storage capacity[5].

(4) Power Management

The intelligent waste bin mainly uses the lithium battery as the power supply source, and a power management module is equipped, in order to meet the need for a long period of stable use of the intelligent waste bin. In addition, there is a warning system inside the power management module. The warning system alarmes when the residual amount of power in the battery of the bin is lower than a set value, to remind people to replace or refill the battery in time.

3. Software Design and Implementation of the Intelligent Waste Bin

3.1. Software Design of the Intelligent Waste Bin

The software plays an important role in realizing the function of intelligence of the garbage bin. This section will provide an overview of the design idea, main functional modules and related technologies involved in the application of the software design concept of the garbage bin[8].

The software of the intelligent garbage bin mainly includes three parts, namely, the image recognition module, classification processing module and interface for users to interact with the program[9].The image recognition module identifies the type of garbage through machine vision technology. The classification processing module then sorts the garbage according to the identification result of the object. Users interact with the intelligent garbage bin through its interface[10].The image recognition process adopts deep learning algorithms to improve the accuracy of recognizing garbage types. In the process of identifying garbage images by using the algorithm of convolutional neural networks (CNN), the model calculates feature quantities .
A simplified representation of the model is shown in the following formula:

$$L(\theta) = \sum_{i=1}^{N} \log(1 + e^{-z_i(\theta)}) \tag{2}$$

Where zi (θ) was the predicted value of the i-th sample, θ represents the model parameters, and N was the total number of samples. The classification processing module needs to classify different types of trash by taking account of practical efficiency while being based on the recognition result of the image recognition module and dealing with various kinds of garbage including recyclables and dangerous items. To increase the efficiency in the implementation of this process in practical applications, the technique of parallel processing can be used to sort garbage faster[10].

The user interaction interface is designed to offer an intuitive and user-friendly experience. It features functions such as displaying waste recognition status, showing classification results, and providing operational guidance. This enables users to easily understand the waste bin's operational status and perform necessary actions.

Next, a code snippet used for waste recognition is presented. The code is written in Python and based on the TensorFlow framework:

```
# Load the pre-trained CNN model from a specified path
model = load_model('path_to_your_model.h5')
def predict_garbage_type(image_path):
    """
    Predicts the type of garbage based on the input image.

    Args:
        image_path (str): Path to the image file.
```

```
        Returns:
            str: Type of garbage (e.g., 'Recyclable', 'Hazardous', 'Organic').
        """
        # Read the image using OpenCV
        image = cv2.imread(image_path)
        # Preprocess the image (resize and normalize)
        processed_image = preprocess_image(image)
        # Use the model to make predictions
        prediction = model.predict(processed_image)
        # Decode the prediction results and return the waste type
        return decode_prediction(prediction)

    def preprocess_image(image):
        """
        Preprocesses the input image by resizing and normalizing it.

        Args:
            image (numpy.ndarray): Input image.

        Returns:
            numpy.ndarray: Preprocessed image.
        """
        # Resize the image to the required dimensions (224x224)
        resized_image = cv2.resize(image, (224, 224))
        # Normalize the image pixel values to the range [0, 1]
        normalized_image = resized_image / 255.0
        return normalized_image

    def decode_prediction(prediction):
        """
        Decodes the prediction results to return the waste type.

        Args:
            prediction (numpy.ndarray): Model prediction output.

        Returns:
            str: Waste type based on the prediction.
        """
        # Get the class index with the highest probability
        class_index = tf.argmax(prediction, axis=1)[0]
        # Define the class labels
        class_labels = ['Recyclable', 'Hazardous', 'Organic']
        # Return the corresponding class label
        return class_labels[class_index]

    # Example usage
    image_path = 'path_to_your_image.jpg'
    garbage_type = predict_garbage_type(image_path)
    print(f"The garbage type is: {garbage_type}")
```

The above design and realization have provided the software part of the intelligent waste bin to realize the function of waste identification and classification, and also realized the function of user interaction, and provide technical support for the intelligence of the intelligent waste bin.

3.2. Software Implementation of the Intelligent Waste Bin

The software implementation of the intelligent waste bin is one of the core links of this design, it processes the information processed by the machine vision module and makes the corresponding decisions. This includes several functions, which are image recognition function, classification processing function, user interaction function and so on.

The image recognition module harnesses cutting-edge algorithms to scrutinize visual data, whereas the classification mechanism guarantees meticulous sorting of waste materials. Meanwhile, the user interaction module enhances the system's accessibility by delivering real-time feedback and operational guidance.

For image recognition, the system deploys deep learning, specifically Convolutional Neural Networks (CNN), to distinguish waste types. The initial preprocessing steps—conversion to grayscale, edge detection, and noise reduction—are designed to augment recognition precision. Subsequently, the preprocessed image is classified using a trained CNN model, which identifies waste based on the extracted features. As depicted in **Fig. 2**, this illustrates the workflow.

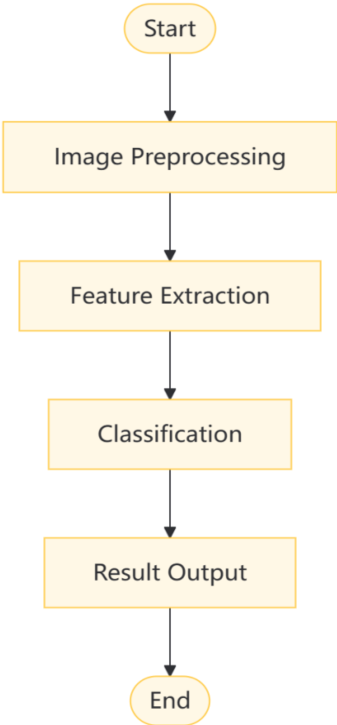

Fig. 2 Image Processing Workflow for Automated Classification

For classification processing, the software must not only identify waste types but also classify them according to established standards. This requires a complex logical judgment to ensure accurate sorting into the appropriate recycling bins.

The user interaction function is designed to make the waste bin more intelligent and user-friendly. Through a touchscreen or voice recognition, users can interact with the waste bin, query waste disposal guidelines, or receive feedback on the waste bin's usage status.

To implement the above functions, the following code snippet has been written, demonstrating how to use the Python language in conjunction with the OpenCV library for image preprocessing and feature extraction:

```
import cv2
import numpy as np
```

```
def preprocess_image(image_path):
    # Read the image
    image = cv2.imread(image_path)
    # Convert to grayscale
    gray_image = cv2.cvtColor(image, cv2.COLOR_BGR2GRAY)
    # Apply Gaussian blur
    blurred_image = cv2.GaussianBlur(gray_image, (5, 5), 0)
    # Edge detection
    edges = cv2.Canny(blurred_image, 50, 150)
    return edges

# Example usage
image_path = 'path_to_your_image.jpg'
processed_image = preprocess_image(image_path)
cv2.imshow('Processed Image', processed_image)
cv2.waitKey(0)
cv2.destroyAllWindows()
```

The above code first reads an image, then converts it to grayscale, applies Gaussian blur to reduce noise, and finally uses the Canny algorithm for edge detection. These are the basic steps of image preprocessing and feature extraction, which lay the foundation for subsequent image recognition and classification.

Through this software part, the intelligent waste bin can recognize and classify waste and provides a friendly user interaction, greatly increasing the practicality and intelligence level of the waste bin[11].

3.3. System Testing

The performance of the intelligent waste bin, which is based on machine vision technology for waste recognition and classification, was evaluated through a series of experimental tests. The experimental setup comprised an STM32 controller, an OV7670 camera, an infrared sensor, and a motor drive module. The software environment utilized Python and OpenCV, with the machine learning model deployed using TensorFlow Lite. The experimental dataset consisted of 200 images, encompassing common waste categories such as plastic bottles, paper, metal, and kitchen waste.

During the experimental process, the system captured images via the camera and subsequently invoked the visual recognition algorithm to perform classification. Following the classification, the control module actuated the motor to deposit the waste into the appropriate compartment. The system's output results were meticulously compared with the manually annotated true categories to determine the classification accuracy. The experimental results indicated that the overall classification accuracy of the system was 87%, with the highest recognition rate for recyclable waste reaching 92%. The recognition accuracy rates for paper and metal waste were 88% and 85%, respectively, while the recognition rate for kitchen waste was relatively lower at 82%.

In terms of stability, the system maintained basic normal operation for 2 hours of continuous running, with only one instance of recognition delay. A comprehensive analysis indicates that the intelligent waste bin can reliably achieve automatic recognition and classification of waste. However, the recognition accuracy decreases under conditions of insufficient lighting, blurred images, or complex waste shapes. Future improvements can be made by introducing a larger training dataset, optimizing image preprocessing methods, and enhancing hardware configuration to boost the system's robustness and adaptability.

4. Conclusion

This study has designed and implemented an intelligent waste bin system based on machine vision. The system captures images of waste through a camera installed at the top of the waste bin, uses a pre-trained convolutional neural network to recognize the type of waste from the captured images, and then drives the actuators (such as servos and motors) to complete the automatic classification and disposal of waste. In terms of hardware, the system has designed a dual-bin structure with recyclable and non-recyclable waste bins. On the software side, the classification model can be trained in real-time to determine the type of waste and control the mechanical devices such as servos to open the corresponding channels and smoothly deposit the waste into the corresponding containers. In addition, the system has also integrated safety functions such as lid opening and anti-pinch hand, ensuring basic human-computer interaction needs and usage safety.

After the system was completed, functional testing and performance evaluation were carried out. During the testing process, recognition and classification tests were performed on various common waste samples (such as paper, plastic, glass, etc.), and the system's response speed and stability were measured. The test results showed that in terms of recognition accuracy, the system achieved a high classification accuracy rate, reaching the level reported in similar solutions in the references (with an accuracy rate of up to 0.99); in terms of response speed, the average time to complete one waste recognition and classification was about 0.95 seconds. The system performed stably in continuous operation tests, without any obvious crashes or malfunctions, and was able to maintain reliable operation for extended periods. Overall, the system has high recognition accuracy and timely response, meeting the expected performance requirements.

Based on the above test results, it can be preliminarily concluded that the intelligent waste bin system has a certain degree of practicality and feasibility. The system has basically achieved the preset functional goals: automatic waste image capture, accurate waste category recognition, and autonomous completion of classification and disposal, meeting the "automatic waste recognition and classification recycling" design requirements. Given that the system is mainly aimed at indoor or small-scale environments, it currently meets the basic waste classification needs. However, considering the influence of factors such as lighting changes and diverse waste types in actual application environments, the system's stability and generalization ability in complex scenarios still have room for improvement. Therefore, it is necessary to further expand the waste image dataset, optimize the algorithm model, and improve the hardware structure design in subsequent work to enhance the system's robustness and recognition coverage.

References

[1] Chen Jiaxin, Zhong Zixin. Design research on intelligent domestic waste bin based on machine vision[J]. Cybersecurity Technology and Application, 2021, (07): 152-153.

[2] Zhou Xuhua, Wu Yimei, Huang Xiaoru, Weng Jiaxin. Design of intelligent waste sorting robot based on machine vision[J]. Equipment Manufacturing Technology, 2021, (08): 22-24+42.

[3] Zhu Weiyi, Wang Xishe, Wu Guanlin. Design of automatic waste classification waste bin based on machine vision[J]. Industry and Technology Forum, 2022, (07): 51-53.

[4] Yang Kaicheng, Shi Yunyang. A new type of intelligent waste bin design[J]. Electromechanical Information, 2019, (33): 142-143. DOI:10.19514/j.cnki.cn32-1628/tm.2019.33.074.

[5] Pan Zhongxun, Ge Yutong, Dong Jingwei, Niu Shuang, Liu Zhenye. Design of intelligent waste bin based on deep learning[J]. Science and Technology Innovation, 2022, (01): 66-68. DOI:10.15913/j.cnki.kjycx.2022.01.021.

[6] Song Tie. Design research on intelligent domestic waste bin based on machine vision[D]. Donghua University, 2019. DOI:10.27012/d.cnki.gdhuu.2019.000245.

[7] Lin Yanmian, Fu Hao, Zheng Guangyan, Zheng Weidong. Design and implementation of intelligent waste bin[J]. Science and Technology Innovation, 2024, (05): 11-14. DOI:10.15913/j.cnki.kjycx.2024.05.003.

[8] Li Meikun, Yang Mingxia, Ling Bin. Design of home intelligent waste bin based on GPU deep learning[J]. Electronic Testing, 2021, (01): 8-11. DOI:10.16520/j.cnki.1000-8519.2021.01.002.

[9] Hu Yao, Wang Dong, Ma Long, Zhang Bin. Design of intelligent waste bin based on image processing[J]. Electronic Testing, 2022, (20): 23-25. DOI:10.16520/j.cnki.1000-8519.2022.20.004.

[10] Song Tao. Design of intelligent waste bin for domestic use based on machine vision[J]. Computer Knowledge and Technology, 2022, (23): 74-75+78. DOI:10.14004/j.cnki.ckt.2022.1576.

[11] Chen Huaiyi, Ye Shuyun, Qiu Zhoupeng, Pan Lihong, Lin Jianzhang, Zheng Zipei, Fu Ruoshui. Design of intelligent waste bin based on voice recognition technology[J]. Computer Programming Skills and Maintenance, 2022, (11): 131-134. DOI:10.16184/j.cnki.comprg.2022.11.049.