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DESIGN AND IMPLEMENTATION OF A MULTIFUNCTIONAL 3D ROBOT FOR KITCHEN WASTE RECYCLING

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Abstract: Currently, household kitchen waste is commonly disposed of either by mixing with other garbage or by directly discharging it into sewer systems. Such practices lead to several environmental and sanitary issues, including contamination of recyclable materials, reduced efficiency of waste sorting, pipe blockages, increased load on sewage treatment facilities, and microbial growth. To achieve on-site, resource-oriented, and high-value utilization of kitchen waste, this paper proposes a multifunctional kitchen robot that integrates kitchen waste processing with 3D printing. The device can directly convert kitchen waste into practical items such as flowerpots, thereby realizing waste reuse and low-carbon environmental goals. Based on the principle of Fused Deposition Modeling (FDM) 3D printing, the robot features improved mechanical structures and feeding methods to enable the use of kitchen waste as a printable material. The integrated system combines automatic crushing, conveying, printing, and self-cleaning functions. The feeding system consists of an extrusion mechanism and a cleaning water pump. The printing unit adopts an MB structure to effectively reduce print bed vibration and improve printing accuracy. The nozzle uses a screw extrusion method, eliminating the traditional heating module and heated bed, thus significantly reducing energy consumption. A dual-chamber isolation design is implemented: the kitchen waste processing module crushes the waste into a slurry and extrudes it for printing. When printing high-structural components, additives can be introduced to enhance mechanical properties, and the printed objects achieve usable strength after natural drying. An independent food printing module, comprising a precise feeding mechanism and a mixing mechanism, enables quantitative proportioning and uniform mixing of ingredients such as flour and sugar for personalized 3D-printed cookies. The two systems operate independently, ensuring hygienic safety. The robot supports both automatic and manual control modes, with adjustable parameters such as crushing duration, water addition, and extrusion speed, offering convenient operation. This robot integrates kitchen waste valorization and multifunctional manufacturing, significantly reducing the volume of household waste requiring collection and transportation as well as associated environmental pollution. It is suitable for households, communities, and educational outreach scenarios such as campus science demonstrations, providing a novel technical solution for low-carbon kitchen waste treatment and home-based smart manufacturing.
Keywords: Kitchen waste; Resource utilization; 3D printing; Household smart device

1 INTRODUCTION

1.1 Research Background and Significance

Household kitchen waste is characterized by large output, high moisture content, and rapid putrefaction. Traditional disposal methods have significant drawbacks: mixing with general household waste reduces the purity of recyclables and increases sorting difficulty; direct discharge into sewers easily causes pipe blockages, increases the load on sewage treatment, and organic matter breeds bacteria, leading to hygienic and environmental risks. With the advancement of waste classification and the "carbon peaking and carbon neutrality" goals, the on-site, resource-oriented, and volume-reducing treatment of kitchen waste has become an important development direction.

3D printing technology offers advantages such as personalized molding, strong material adaptability, and convenient operation, providing a new pathway for kitchen waste reuse. This paper integrates kitchen waste pretreatment with 3D printing to design a multifunctional robot that can directly convert kitchen waste into practical items such as flowerpots, while also being compatible with food printing. Combining environmental protection with practicality, this device holds significant value for promoting low-carbon household waste treatment and popularizing the concept of a circular economy.

1.2 Current Research Status at Home and Abroad

Currently, kitchen waste treatment technologies both domestically and internationally mainly rely on methods such as aerobic composting, mechanical shredding with direct discharge, and anaerobic fermentation. These methods generally suffer from drawbacks including large footprint, long treatment cycles, complex operation and maintenance, and secondary pollution problems such as leachate and odor generation, making them difficult to adapt to the household scenarios requiring small-scale, on-site, clean treatment [1-2].

In the field of 3D printing, existing research and products are mostly focused on printing with industrial-grade polymer filaments and standardized food ingredients. Dedicated 3D printing equipment for household kitchen waste in slurry form is rarely studied [3-4]. There is a lack of fully integrated designs encompassing crushing, pulping, conveying, printing, and automatic self-cleaning. Furthermore, integrated equipment that features both a dual-system isolation design (for kitchen waste-based printing and food printing) is even rarer [5].
To address these gaps, this paper focuses on household application scenarios to develop a low-cost, low-power, multifunctional 3D printing device for kitchen waste, aiming to overcome the shortcomings of existing technologies regarding on-site resource utilization of household kitchen waste.

2 OVERALL SCHEME AND WORKING PRINCIPLE

2.1 Design Objectives

(1) Achieve full-process automation of on-site crushing, pulping, conveying, printing, and cleaning of kitchen waste.
(2) Adopt a heating-free screw extrusion mechanism and an MB structure to reduce power consumption and improve printing stability.
(3) Ensure complete isolation of the dual systems to guarantee hygienic safety for both kitchen waste printing and food printing.
(4) Support automatic/manual modes, adjustable parameters, and AI voice assistance to accommodate household use.

2.2 Working Principle

This design references the FDM principle while reconstructing the feeding and extrusion mechanisms. Kitchen waste enters the crushing chamber through an inlet, where high-speed blades crush it into a slurry. A screw-driven slide table then extrudes and conveys the slurry to the printing unit. The MB-structured frame reduces print bed vibration, and four stepper motors drive the XYZ axes and the extrusion mechanism. The screw extrusion ensures uniform material output and rapid response. For printing high-strength models, additives such as fine sand or a small amount of cement can be introduced to enhance mechanical properties, and the printed objects meet usage requirements after natural drying. The food printing module operates independently with its own feeding, mixing, and conveying systems, physically isolated from the kitchen waste system to ensure hygiene.

2.3 Overall Scheme

The proposed multifunctional kitchen waste 3D printing robot is designed with the core objective of on-site resource utilization of household kitchen waste. It integrates kitchen waste pretreatment, 3D printing, food printing, and intelligent control. The overall design follows the principles of dual-system isolation, integrated workflow, and low-power structure, enabling efficient conversion of kitchen waste into practical items such as flowerpots while also offering personalized food 3D printing functionality.
The system consists of two independent modules: the kitchen waste processing system completes the full-process operations of automatic crushing, pulping, conveying, printing, and cleaning; the food printing system achieves precise ingredient dispensing, mixing, and molding. The two systems are physically isolated to ensure hygienic safety.
The control system is based on the Marlin firmware, equipped with A4988 driver modules and a 1.8-inch TFT color screen, supporting both automatic and manual operation modes. A screw extrusion mechanism is adopted, and the traditional heating module is eliminated, significantly reducing power consumption. Additives can be incorporated to enhance the strength of printed objects, and a PTC heating fan is provided to prevent collapse of tall models. The device integrates an AI intelligent voice assistant to provide operational guidance and ingredient ratio inquiries. The overall scheme meets the requirements of low cost, easy operation, cleanliness, and multifunctionality for household scenarios.

3 MECHANICAL SYSTEM DESIGN

3.1 Overall Structure

The complete machine consists of a body frame, a kitchen waste processing system, a food processing system, a printing execution system, a cleaning system, and an intelligent control system. The structure is compact and suitable for household placement. The detailed structural design is shown in Figure 1.

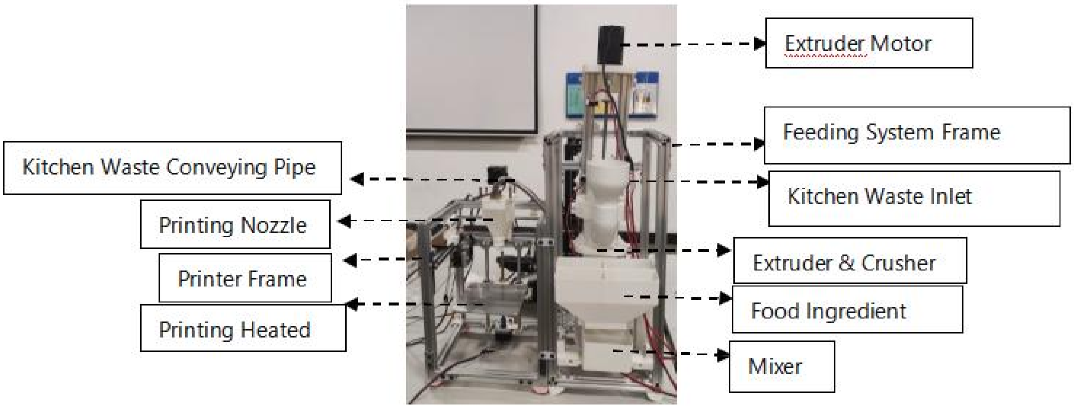


Figure 1 Corresponds to the Structural Diagram of the Robot

3.2 Detailed Mechanical System Design

3.2.1 Right side: kitchen waste processing and extrusion unit

(1) Extruder Motor

Function: Provides power to the screw extrusion mechanism, controls the material extrusion speed and flow rate, and serves as the core power source for conveying kitchen waste slurry.

Working Principle: The motor directly drives the screw to rotate via a coupling. Utilizing the helical angle of the screw, an axial thrust is generated to uniformly and stably push the crushed kitchen waste slurry forward, achieving quantitative extrusion.

(2) Feeding System Frame

Function: Provides stable support for the kitchen waste inlet, crusher, and extruder, ensuring coaxial alignment and operational stability of each component while suppressing vibration.

Working Principle: The frame is constructed using modular aluminum profiles. Each functional module is fixed via fasteners, forming an independent vertical feeding channel. It is physically connected to the left-side printing system but structurally maintainable separately, preventing interference with feeding accuracy caused by printing motion.

(3) Kitchen Waste Inlet

Function: Serves as the feeding channel for kitchen waste, allowing users to conveniently deposit pre-processed kitchen waste while minimizing odor diffusion.

Working Principle: A funnel-shaped design allows material to fall naturally into the crusher below by gravity. A splash guard prevents material splashing during crushing. The inlet can also serve as a water addition port to assist in adjusting the material moisture content.

(4) Extruder and Crusher

Function: The core composite unit for kitchen waste treatment, responsible for crushing, pulping, and preliminary conveying of materials.

Working Principle:

① Crushing stage: Built-in high-speed rotating blades chop and grind the input kitchen waste (fruit peels, leftovers, etc.) into a fine slurry.

② Extrusion stage: After crushing, the material falls into the lower screw extrusion chamber, where the screw pushes it toward the outlet, providing a continuous slurry stream for subsequent printing.

(5) Food Ingredient Dispenser

Function: The raw material supply unit of the food printing system, physically isolated from the kitchen waste system, enabling quantitative dispensing of ingredients.

Working Principle: A multi-channel roller-type dispensing structure is adopted. A geared motor drives the rollers to rotate, allowing ingredients such as flour, sugar, and chocolate powder to be dispensed according to preset weights. This precisely controls ingredient ratios and avoids manual operation errors.

(6) Mixer

Function: The material mixing unit of the food printing system, blending ingredients with liquids (water/oil, etc.) into a uniform, printable batter.

Working Principle: A built-in mixing rod is driven by an independent motor to rotate, mixing the dispensed ingredients thoroughly. This ensures uniform batter composition without lumps, preventing nozzle clogging and uneven extrusion during printing.

3.2.2 Left side: 3D printing execution unit

(1) Kitchen Waste Conveying Pipe

Function: Connects the kitchen waste extruder to the printing nozzle, enabling sealed transport of the slurry material.

Working Principle: Made of food-grade, corrosion-resistant material with a fully sealed design, the pipe stably conveys the kitchen waste slurry output from the extruder to the printing nozzle while preventing material drying and odor leakage, thereby maintaining material fluidity.

(2) Printing Nozzle
Function: The final extrusion actuator for kitchen waste/food materials, completing 3D shaping along a preset path.
Working Principle: A heating-free screw extrusion structure is adopted. The nozzle orifice diameter can be changed according to molding requirements (e.g., 4 mm/5 mm). The screw rotates to extrude the slurry/batter delivered by the conveying pipe. The nozzle moves in the XY axes to achieve layer-by-layer stacking. The elimination of the traditional FDM heating module significantly reduces equipment power consumption.
(3) Printer Frame
Function: Provides motion support for the printing nozzle and the printing heated bed, ensuring stability and accuracy during the forming process.
Working Principle: An MB structure is adopted, composed of aluminum profiles, smooth rods, and pulleys. A belt drive achieves smooth XY-axis motion, while a screw-driven lift controls the Z-axis. This effectively reduces shaking and vibration during printing, improving the forming accuracy for non-standard materials such as kitchen waste slurry.
(4) Printing Heated Bed
Function: Serves as the forming platform for 3D printing, providing a stable support surface to assist material adhesion and drying.
Working Principle: The kitchen waste slurry/batter extruded from the nozzle is deposited directly onto the heated bed. The first layer achieves initial adhesion relying on its own moisture content. After printing, an auxiliary fan accelerates drying. In some scenarios, a low-temperature heating module may be added to improve material solidification speed and forming stability.

3.2.3 Overall system collaborative working logic

(1) Kitchen Waste Printing Workflow
Material input via inlet → Crushing into slurry by crusher → Slurry pushed by extruder → Conveyed to nozzle via conveying pipe → Extruded and shaped by nozzle following the toolpath → Dried and solidified on heated bed.
(2) Food Printing Workflow
Quantitative ingredient dispensing by dispenser → Mixing into batter by mixer → Independent conveying path to nozzle → Extrusion and shaping. The entire process is physically isolated from the kitchen waste system to avoid cross-contamination.

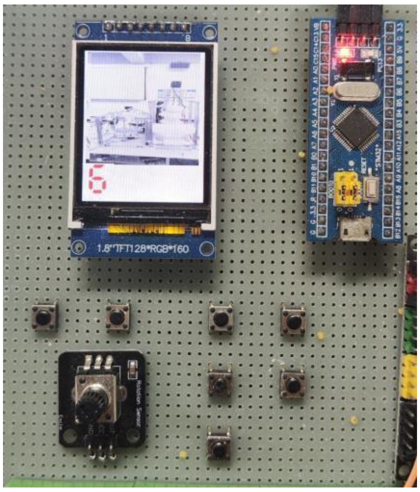
4 CONTROL SYSTEM DESIGN

4.1 Implementation Structure for Kitchen Waste 3D Printing

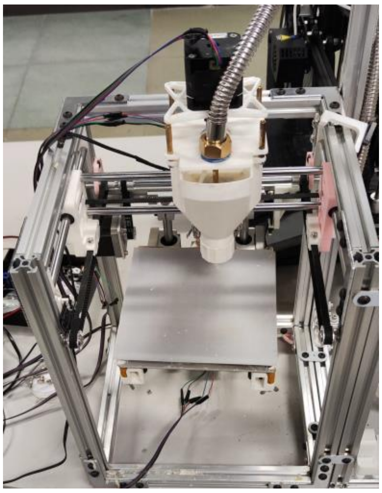
The printing unit adopts an MB structure, which significantly reduces the shaking of the heated bed. Four stepper motors drive the XYZ axes and the extruder, controlled by A4988 driver modules. The Z-axis uses a screw-driven lift, while the XY axes employ belt drives. Four smooth rods and eight pulleys minimize friction. Three limit switches complete the homing positioning. The extrusion mechanism consists of a mixing rod, a screw, and an extrusion stepper motor. The mixing rod ensures material uniformity, the screw achieves stable extrusion, and the nozzle supports interchangeable diameters of 4 mm and 5 mm.

4.2 Implementation Principle of Kitchen Waste 3D Printing

Referring to the control module and printer structure illustrated in Figures 2 and 3, kitchen waste enters the crusher through the inlet and is crushed into a slurry. The slurry then enters a cylindrical storage tank with a diameter of 10 cm. Inside the tank, a screw transmission mechanism pushes the slurry via a piston-type extrusion through a conveying pipe to the printer nozzle, achieving continuous supply of the kitchen waste material.
The printer main body adopts an MB-structured frame, which greatly reduces the shaking of the printing heated bed during motion and improves forming stability. The entire machine uses four stepper motors to drive the XYZ axes and the extrusion mechanism, with the motors precisely controlled via A4988 driver modules. The Z-axis (heated bed) moves vertically using a screw drive, while the XY axes achieve planar motion through belt drives. Four smooth rods serve as guide rails, paired with eight pulleys to reduce running friction. Three limit switches complete the printer's homing positioning, providing a reliable reference for the forming process.
As shown in Figure 2, the control module consists of a main control board, a TFT display screen, and a keypad unit. The printer extrusion mechanism adopts a screw extrusion method. Compared with the traditional FDM plunger-type extrusion, this design significantly improves material uniformity and response speed, eliminates extrusion start/stop delays, and prevents abnormal extrusion volumes from affecting model appearance. The control system uses the Marlin firmware, which is commonly used in the 3D printing field, adapted to the motion control logic of the screw extrusion and MB structure, achieving coordinated multi-axis motion and precise extrusion volume adjustment.
To address the issue of collapse susceptibility during the forming of kitchen waste slurry, this design proposes an additive reinforcement scheme. When printing relatively tall models, an appropriate amount of fine sand or a small quantity of cement can be added to the kitchen waste slurry to enhance material support and prevent model collapse during printing. After printing, the model is naturally dried and cured. The cement component hydrates and hardens, enabling the finished product to achieve the strength and hardness required for application scenarios such as flowerpots, thereby realizing the transformation of kitchen waste into practical items.

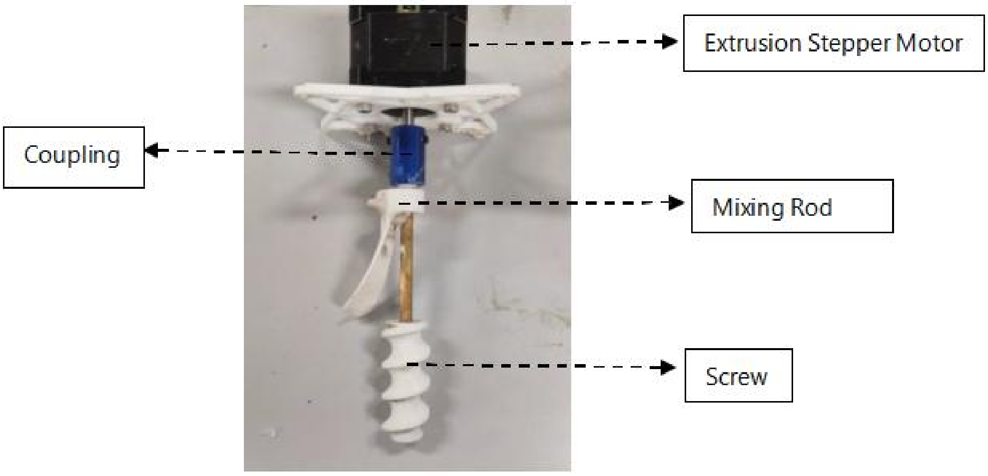


Figures 2 Correspond to the Control Module



Figures 3 Printer Structure

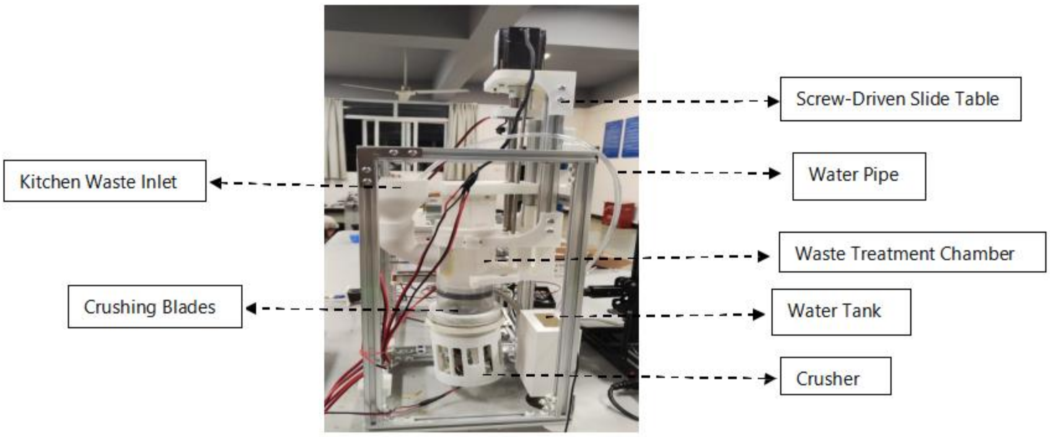
By controlling the rotational speed of the screw and changing the nozzle orifice diameter, different printing speeds can be achieved. The mixing rod is responsible for uniformly stirring the printing material, while the screw extrudes the material. Models with different layer heights can be printed. The nozzle orifice diameters are 4 mm and 5 mm, which can be interchanged according to requirements, as shown in Figure 4.



Figures 4 Nozzle Details Respectively

4.3 Kitchen Waste Processing System

After kitchen waste enters the treatment chamber through the inlet, the crusher first drives the crushing blades to rotate at high speed, breaking down large pieces of material into a uniform slurry. Subsequently, the screw-driven slide table pushes the slurry through a piston-type extrusion to the printer for shaping. The system can preset the crushing duration and the water-to-material ratio. During the crushing process, it automatically adjusts the crusher speed and the amount of water added, achieving precise control over the material's moisture content and uniformity. After the printing task is completed, the system automatically rinses the chamber and pipelines through a cleaning circuit composed of a water pipe and a water tank, and discharges the wastewater, effectively preventing material residue and odor generation, thereby improving equipment cleanliness and user experience (Figure 5).



Figures 5 Correspond To The Processing System

The corresponding working mode can be selected via the control board, including automatic crushing and extrusion mode as well as automatic cleaning mode. Different modes can be selected via the 1.8-inch TFT color screen. In the automatic crushing and extrusion mode, if the printing material is too viscous or contains excessively large particles, the user can switch to manual mode to adjust the water addition and increase the crushing time using the buttons. When printing tall models, the heating fan can be activated via the buttons to provide simultaneous drying during printing, ensuring that the upper layers of the model do not collapse.

After the model is printed, the automatic cleaning mode can be selected. The piston in the waste treatment chamber rises upward, and the water pump fills the chamber with cleaning water. The crusher drives the blades to rotate at high speed, causing the water to swirl and rinse away kitchen waste residue remaining on the inner walls of the waste treatment chamber. The piston then pushes downward to expel the wastewater, completing the flushing process (Figure 6-7).

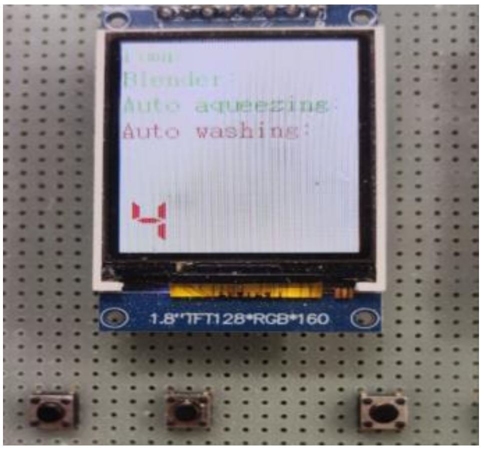
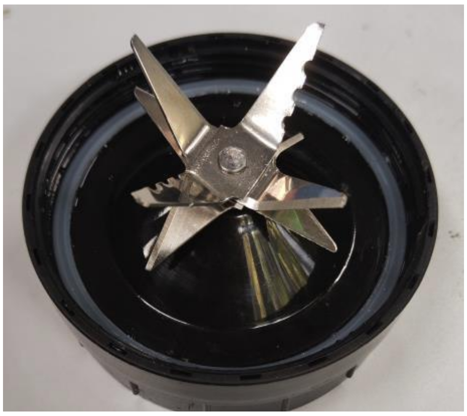


Figure 6 Mode Selection



Figures 7 Double-Layer Shredding Blades

4.4 Food Material Processing System

The printer is capable of printing not only processed kitchen waste but also using kitchen ingredients as raw materials. Ingredients such as flour, sugar, and chocolate powder can be used to print cookies in various shapes. After printing, the cookies are placed in an oven to obtain edible 3D models. Figure 8 shows the specific structure of the food material processing system.

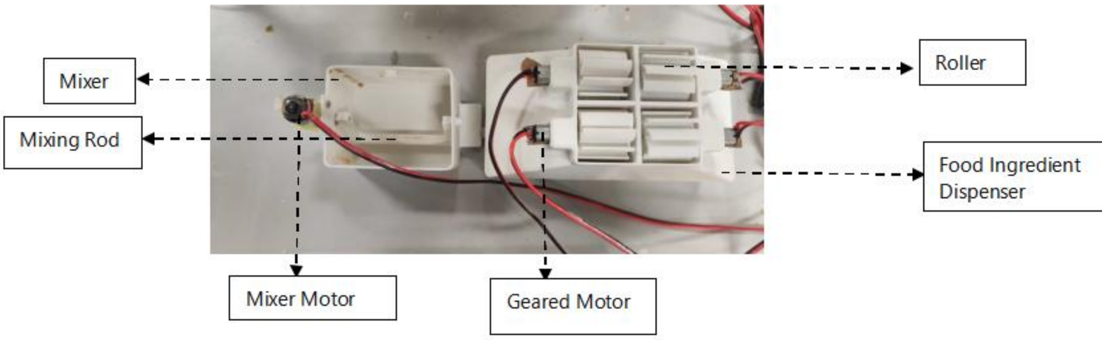


Figure 8 Corresponds to The Food Ingredient Processing System

In the food ingredient dispenser, rollers are responsible for dispensing the ingredients. Four geared motors drive the rollers to rotate. By inputting the desired grammage of ingredients via the control board, the food ingredient dispenser can accurately dispense different portions of ingredients. Below the food ingredient dispenser is the mixer, which receives the ingredients conveyed from the dispenser and mixes them uniformly with liquids such as water. The dispensing weight, mixing time, and water quantity can be selected via a knob. By controlling the motor speed and rotation duration, precise dispensing of ingredients can be achieved.

4.5 AI Intelligent Voice Assistant Module

To enhance operational convenience and lower the usage threshold for household users, the system is equipped with an AI intelligent voice assistant module. Built upon the DeepSeek model, this module integrates the complete user manual, operating procedures, and safety precautions for the device, enabling real-time responses to user voice inquiries. When users encounter operational difficulties during the printing process, they can obtain guidance on device usage, parameter settings, and troubleshooting through voice interaction. In the food printing mode, users can query the formulation ratios and mixing parameters for ingredients such as flour, sugar, and chocolate powder. The module provides accurate and real-time intelligent assistance, significantly improving the human-computer interaction experience and device usability [6]. This module requires no complex operations, lowers the usage threshold, and enhances the overall intelligence and household-friendliness of the machine (Figure 9).

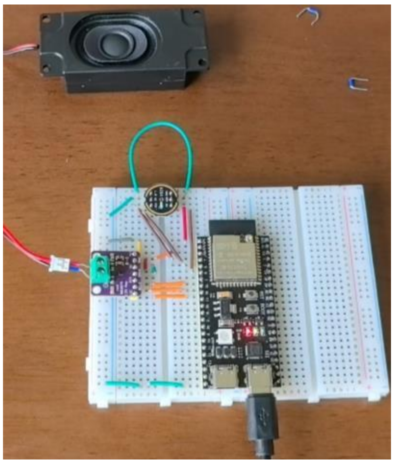


Figure 9 Corresponds to the AI Smart Voice Assistant Interface

5 CONCLUSION

Aiming at the pain points of household kitchen waste disposal, this paper has designed a multifunctional 3D printing robot that integrates kitchen waste resource utilization and food printing functions [7][8]. The device innovatively adopts a heating-free screw extrusion mechanism and an MB frame structure, eliminating the traditional FDM heating module and significantly reducing equipment power consumption [9]. Through an integrated workflow of crushing, pulping, conveying, printing, and cleaning, the device achieves on-site conversion of kitchen waste into practical items such as flowerpots. At the same time, a physical isolation design between the kitchen waste system and the food system ensures hygienic safety while enabling personalized food 3D printing. Prototype testing shows that the device operates stably with good forming performance, effectively reducing the volume of kitchen waste requiring collection and transportation as well as associated environmental pollution, offering both environmental and practical value. This study provides a novel technical solution for low-carbon household kitchen waste treatment and small-scale smart manufacturing, demonstrating promising prospects for widespread application [10].

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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