Undergraduate Graduation Project (Thesis)

Design and Application Research of Embedded Multi-Material 3D Printing System

Abstract

Embedded 3D printing technology is an emerging manufacturing technology that allows nozzles or tips to directly print "ink" into "support material" to complete the printing of soft materials. This project mainly studies the design and application of embedded multi-material 3D printing system. Compared with single-material printing, multi-material printing requires automatic nozzle replacement during the printing process to complete material replacement, which requires designing specific mechanical structures and programs for the printing system.

In terms of mechanical structure, this project builds a 3D printer based on the CoreXY framework and designs a nozzle replacement device that uses a cable transmission device to convert the fixed torque to lock and unlock the nozzle. The nozzle uses a lead screw drive to push the syringe to extrude the material.

In terms of control system, this project uses a Raspberry Pi as the upper computer, the 3D printer motherboard BIGTREETECH Octopus Pro as the lower computer, and uses Klipper firmware to control the embedded multi-material 3D printing system. By adding tool lock and other function functions in the Klipper configuration file, the 3D printing system has the function of printing multiple materials at the same time.

In terms of material preparation, ethylene silicone oil, hydrogen-containing silicone oil, and platinum catalyst are used to synthesize addition-type RTV silicone rubber as the support mechanism, and catalyst ink and conductive ink are prepared using platinum catalyst.

To verify the usability of the 3D system, the project used the printer to print vertical and horizontal color alternating cube and tension sensor. The printing results showed that the printing system can perform stable multi-material 3D printing. In future research work, we will increase the number of nozzles to realize the printing of more types of materials and complete products with more complex structures and functions.

Keywords: Embedded multi-material 3D printing system; nozzle replacement; Klipper firmware; RTV silicone rubber

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Introduction

1.1 Background and research significance

3D printing technology is a manufacturing technology that converts digital models into physical models, also known as additive manufacturing technology. It uses computer-aided design (CAD) software to convert the digital model into a slice file and send the slice file to a 3D printer. The 3D printer adds material layer by layer according to the specified path and layer, and gradually builds a physical model. 3D printing technology can use a variety of materials for printing, and different printing materials can meet different manufacturing needs. For example, plastic materials are often used to make complex mechanical parts and small parts[1], while metal materials are suitable for the manufacture of high-strength parts and tools. Biomaterials are used to make models of human tissues and organs. 3D printing technology has a wide range of applications in various fields, such as medical, automotive, manufacturing, and education, among others. It can be used to manufacture complex mechanical parts, high-strength parts, prototypes and models, tools and jigs, personalized medical devices, artificial organs and tissues, and more[2]。 The development of 3D printing technology is also constantly expanding its application range, making it play an increasingly important role in the field of manufacturing.

In recent years, the application of 3D printing technology to soft robot applications has become a new trend[3]。 A soft robot is a flexible and malleable robot that can complete a variety of different tasks, such as moving, grabbing, deforming, etc. Compared with traditional hardware robots, soft robots are more adaptable and flexible. Therefore, soft robots have a wide range of application prospects in medical treatment, rescue and other fields. 3D printing technology can be used to manufacture key components such as exoskeletons, muscles, and sensors for soft robots, and can also be used to customize soft robots of different shapes and sizes[4]。

The application of 3D printing technology in soft robot manufacturing is mainly reflected in the following aspects: manufacturing soft robot exoskeleton: exoskeleton is an important part of soft robot to achieve movement and deformation. Exoskeletons of various shapes and sizes can be manufactured through 3D printing technology, and parameters such as materials and thicknesses of the exoskeleton can be controlled to meet the needs of different tasks. In addition, 3D printing technology can also create complex exoskeleton structures to enhance the movement and deformation capabilities of soft robots. Manufacturing soft robot muscles: The muscles of soft robots are usually made of various flexible materials, such as air pressure, electrical actuation, shape memory alloys, etc. These materials can be fabricated by 3D printing technology, creating muscles with multi-layered structures and complex shapes to enable the movement and deformation of soft robots. Manufacture of soft robot sensors[5]: Sensors in soft robots are mainly used to perceive and interact with the surrounding environment[6]。 Sensors of various shapes and materials, such as stretch sensors, can be manufactured through 3D printing. In addition, 3D printing technology can also fabricate sensors with multi-scale structures to enhance the perception of the environment of soft robots.

On the other hand, the development of 3D printing technology also provides new possibilities for the manufacture of soft robots. The manufacture of soft robots requires the use of flexible materials[7], and special structures need to be made for it. These requirements are very difficult to meet in traditional manufacturing methods, which make it difficult to precisely control the shape and structure of the material. 3D printing technology, on the other hand, can directly convert design files into physical models, so the shape and structure of materials can be controlled very accurately, so as to achieve the precise manufacturing of flexible materials and special structures required for soft robots. In addition, the customizability of 3D printing technology also brings great benefits to the manufacture of soft robots. The shape and size of soft robots often need to be designed according to the needs of specific applications, so the shape and size of the robot need to be flexibly customized. This flexible customization is difficult to achieve with traditional manufacturing methods, as the manufacturing process needs to be redesigned for each robot of different shapes and sizes. 3D printing technology can realize the rapid manufacturing of soft robots of different shapes and sizes by simply modifying the design files.

In order to better support the production of flexible robots, embedded 3D printing came into being. Embedded 3D printing technology is an emerging manufacturing technology, this printing strategy allows the nozzle or tip to print the "ink" directly into the "support material" to complete the printing of soft materials[8]。 The biggest difference between embedded 3D printing and current material extrusion methods is that the printing medium is not air, but a support matrix with unique rheological properties. Since non-covalent and reversible bonds can be broken by shear stress stimuli, direct writing based on the support medium is feasible. When the nozzle passes through the medium, the medium immediately reforms the bonds. Due to its rheological properties, the printed ink is suspended in a support matrix. Even with suspended structures, no additional support is required during the printing process. In contrast to fused deposition modeling and stereolithography, embedded 3D printing strategies can be brace-free. This feature improves the stability of printing and simplifies pre-processing. Embedded 3D printing technology for soft materials has been applied in many fields. For example, in healthcare, the technology can be used to create bendable earplugs or flexible prosthetics to suit different body shapes and needs. In the field of robotics, this technology can be used to create flexible sensors and manipulators, making robots more flexible and adaptable. In the industrial sector, embedded 3D printing of soft materials can be used to manufacture flexible seals or vibration dampers to suit different environments and applications.

This project mainly focuses on the design and application of embedded multi-material 3D printing systems. Multi-material 3D printing technology has many advantages over single-material printing. Multi-material 3D printing technology enables the use of different materials in the same construction process, allowing for the creation of objects with more complex structures and morphologies. This technology can make the products produced have higher practical value and can also meet the needs of a wider range of applications, such as medical, automotive, electronics, biology and other fields. The use of a variety of materials allows for enhanced performance and customizability of 3D printed products. For example, by using materials of different hardness and strength, the product can be made with better compression and bending resistance; The use of materials with different properties can make the product more resistant to heat and corrosion. Multi-material 3D printing technology can complete multiple processes in the same build process, which can improve production efficiency and reduce production costs. At the same time, the amount of material used and production costs can be reduced due to the reduction of material waste in the manufacturing process.

1.2 Research status at home and abroad

Flexible robotics is a fast-growing field with revolutionary automation potential. In contrast to rigid robots, flexible robots have an inherently soft and stretchable body that is capable of deforming and absorbing collision energy. Flexible robots are typically made of soft, superelastic materials and are driven by sequential inflation of the internal cavity. This muscular simulation of the driving style results in an incompletely driven structure with infinite degrees of freedom, enabling a wide range of complex movements. This feature enables these systems to adapt to their surroundings and enable safe human-machine interaction. However, it also adds complexity in design, manufacturing, and control. Despite these challenges, flexible robots have potential in many common application areas, including wearable systems, haptics, and surgical devices.

Soft robots are mainly composed of fluids, gels, functional polymers, and other deformable substances. These materials exhibit elastic and rheological properties similar to those of soft biomass, allowing the robot to remain operational when stretched and squeezed. What's more, all of these materials are compatible with current 3D printing technologies. Traditional soft robotic manufacturing methods involve mold making and casting, but 3D printing technology is now increasingly being used because 3D printing is faster and more reliable. Therefore, the development of soft robots is inseparable from the development of soft material 3D printing technology, multi-material 3D printing technology, and embedded multi-material 3D printing technology, which has also attracted the attention of many scholars at home and abroad.

1.2.1 3D printing technology for soft materials

Soft material 3D printing technology refers to the manufacturing technology that uses a specialized 3D printer and soft material to make soft structures and devices by stacking, positioning and extruding soft materials layer by layer. Unlike traditional 3D printing, soft material 3D printing technology uses materials that are usually highly soft, stretchable, and deformable, such as gels, fluids, or elastic polymers. 3D printing technology for soft materials can be used to make many different types of soft robots. These robots usually consist of multiple elastic components that can be controlled by hydraulic or pneumatic pressure. In addition, 3D printing technology of soft materials can also be used to manufacture various flexible sensors and flexible circuit boards. These devices are typically made of highly flexible materials and can be designed to measure physical quantities such as force, pressure, deformation, and can enable complex movements such as bending, torsion, stretching, etc. These devices can be used in many fields such as medical, biomedical, sports health monitoring, virtual reality, etc.

2017 UC San Diego Dylan Drotman developed oneThe 3D-printed robot, with its corrugated soft legs rotating in two axes, can walk on rough terrain that previously posed a significant challenge to the soft robot. They provided a model and finite element simulation of the soft-leg module and predicted the robot's kinematics. The driving characteristics of these modules were simulated by using finite element analysis, and the results of the analysis and calculations were compared with the experimental results of the tethered prototype. The experimental soft robot was able to lift its legs up to 5.3 cm and was able to reach a maximum speed of 20 mm/s (0.13 steps/s). This study represents a practical approach to the design and fabrication of functional mobile soft robots using soft 3D printing technology[9]。

Figure 1-1 Side view of soft quadruped walking on rocky terrain[8]

In 2017,J. Plott and A. Shih proposed a new extrusion-based type based on the shortcomings of the traditional liquid phase injection molding manufacturing method in terms of flexible pneumatic actuatorsThe processing method of 3D printing technology enables the fabrication of solid and thin-walled structures without voids for the additive fabrication of extrusion-based moisture-curing silicones. The development of this technology is of great significance for achieving high-precision manufacturing of soft materials, especially in applications such as flexible robots[10]。 In 2022,Théo Calaiset al. proposed a new type of free fluid 3D printing technology, which uses flexible materials and high-precision machine control to print high-precision flexible components in 3D space, thus providing new ideas and methods for the manufacture of soft robots[11]。 In 2022, Zhenhua Wang et al. introduced a simple multi-material bonding direct ink writing (MJDIW) printing method. This method enables true free-form 3D printing to fabricate fully soft actuators and robots with complex 3D structures, while integrating materials with different mechanical properties to expand the manufacturing capabilities of additive manufacturing methods[12]。

1.2.2 Multi-material 3D printing technology

Multi-material 3D printing technology is a technology that uses multiple materials at the same time to manufacture an object on the same 3D printing platform. This technology makes it easier to fabricate objects with complex structures and enables different physical and chemical properties to be combined with each other. Multi-material 3D printing typically uses two or more materials that can be combined as per the design requirements, for example, when printing an object, one material can be used to make its outer structure, while the other material is used to make the internal structure. Multi-material 3D printing technology is still in its early stages of development, and researchers are constantly exploring new materials and technologies to better meet the needs of different application fields.

In 2018, the Sodupe-Ortega E team investigated the impact of the main parameters driving multi-material 3D bioprinting and proposed a method to calibrate these systems and accurately control the print resolution, helping to advance the creation of complex 3D structures and vascular networks for tissue engineering[13]。 Conrad et al. proposed a new multi-material 3D printer with on-demand tool change characteristics. The device is capable of processing multiple substances in a single print by switching between tools at runtime[14]。 M. Lanaro proposed a user-centered 24D printer system design, capable of processing a wide range of biomaterials using a variety of technologies, and demonstrated the ability to fabricate a variety of popular extrusion and galvanic kinetics-based scaffolds on flat plates and rotary collectors[15]。

Shanghai Jiao Tong University, 2020Ningbin Zhanget al. designed and fabricated modular pneumatic actuated brakes, called RFiSFAs, through multi-material 3D printing. It has:The characteristics of both rigidity and softness，Human-like hands can be generated directly and modularly. The RFiSFA has a bio-inspired hybrid structure that integrates a pneumatic corrugated cavity and an articular skeleton. The experimental results showed that the manufactured hands were able to withstand appropriate hammering blows under pneumatic control and were able to grasp objects of different sizes, shapes, and textures[16]。

1.2.3 Embedded multi-material 3D printing

Prototypes of embedded 3D printing technology first appeared in the manufacture of some simulated blood vessels, which was referred to in the early literature as "direct writing". One of the first studies demonstrating embedded 3D printing technology was conducted by Lewis et al. in 2004, who used embedded 3D printing technology for direct writing of 3D meshes[8]。 Kolesky and Truby et al. report a novel approach to create vascularized heterogeneous tissue structures on demand through embedded multi-material 3D. They prepared gelatin methacrylate (GelMA) as a support medium and a cell carrier as a cell matrix. This material was chosen for its low cost, ease of availability, ease of processing, and biocompatibility. GelMA is a denatured collagen with a photopolymerizable methacrylate (MA) band that allows the carrier media to be photocross-linked by UV light after printing. The gelation process comes from intermolecular triple helix assembly, and its molecular structure is not much different from that of collagen. This scalable platform allows for the production of complex tissue structures and programmically printing of vascular systems and various cells into support media[17]。

In 2020, Guangda Chen et al. developed a functional material by combining the structure of 3D printed hydrogels with enzyme-induced biomineralization. Combined with embedded 3D printing, complex and mineralized free-form buildings are created without sacrificing ink. The study provides a viable approach to fabricate composites with high-fidelity architectures and customized mechanical properties, opening the way for next-generation functional materials and structures by combining 3D printing with biomineralization[18]。

1.3 The main research content of the project

Firstly, an embedded multi-material 3D printer was designed and manufactured to achieve hybrid printing and high-precision positioning of multiple materials. This includes selecting the right components such as the drivetrain, positioning system and printhead to ensure the stability and efficiency of the system. Based on the control firmware Kilpper and software Solidworks, it realizes the functions of multi-material design, slicing and printing. It also needs to be compatible with hardware systems. Secondly, for multi-material printing, the printing parameters of different materials need to be optimized to ensure that the printing quality of each layer is stable and there will be no inter-layer peeling or other quality problems. Finally, the embedded multi-material 3D printer was used to complete the printing of the multi-material design, and the feasibility of the printing system was tested.

1.4 Essay structure

This article is divided into six chapters. The first chapter briefly describes the research background and significance of multi-material embedded 3D printing. The second chapter introduces the design of an embedded multi-material 3D printing system from the aspect of printer mechanical structure design. The third chapter describes the control system of the printer from the firmware aspect. Chapter 4 describes material preparation for embedded 3D printing. The fifth chapter is the operation of the multi-material 3D printing system and the analysis of experimental results. Chapter 6 summarizes the work of the study and proposes prospects.

Mechanical structure of an embedded multi-material 3D printing system

2.1 3D printer frame structure

The 3D printer frame structure refers to the supporting structure of the 3D printer, which determines the printing accuracy, printing speed, printing height, stability and maintainability of the 3D printer[19]。 According to different motion modes and structural forms, the mainstream 3D printer frame structure includes Cartesian coordinate system frame, Delta frame, CoreXY frame, and SCARA frame.

2.1.1 Cartesian coordinate system frame

The Cartesian coordinate system is one of the most common frame structures in 3D printers[20]。 The characteristic of this structure is that it is based on the Cartesian coordinate system of the three-dimensional coordinate system to control the movement of the print head. In the Cartesian coordinate system frame, the print head moves in the X, Y, and Z directions, while the print bed moves in the Z direction. See Figure 2-1The Cartesian coordinate system frame is usually composed of a linear guide rail and a linear bearing, where the linear guide is used to support the movement of the print head and the linear bearing is used to support the movement of the print bed. In a Cartesian coordinate system frame, the movement of the printhead and print bed is controlled by a set of motors and rail assemblies.

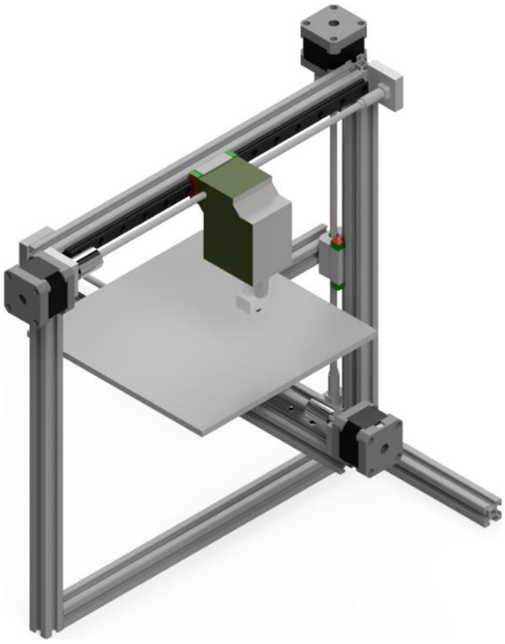


Figure 2-1 Cartesian coordinate system frame

One of the advantages of Cartesian coordinate system frames is their ease of maintenance and repair. Since the structure is relatively simple, it is relatively easy to operate when it comes to maintenance and repair. In addition, Cartesian frames are faster and more accurate because the rails and bearings provide more stable support, which reduces vibration and sloshing and improves print quality.

2.1.2 Delta frame

In the market, there is a very common structure, which is called the parallel arm structure[21]。 It was originally used to make mechanical claws that could quickly and precisely grasp small and light objects. Robots with this structure are called parallel robotic arms. The parallel mechanism is a new type of mechanism that appeared in the 90s, and has become an important part of modern industrial robots due to its characteristics of high speed, high precision and high flexibility.

See Figure 2-2In the Delta frame, three motion arms are distributed at a 120-degree angle on top of the printer, and each motion arm has a motor and a bracket to support the movement of the print head. The printhead is positioned by telescoping the moving arm to construct the 3D print. Delta frames typically use a triangular bracket and ball head connector to achieve the telescoping of the motion arm, which allows the printhead to move at any angle, allowing for high-precision printing[22]。

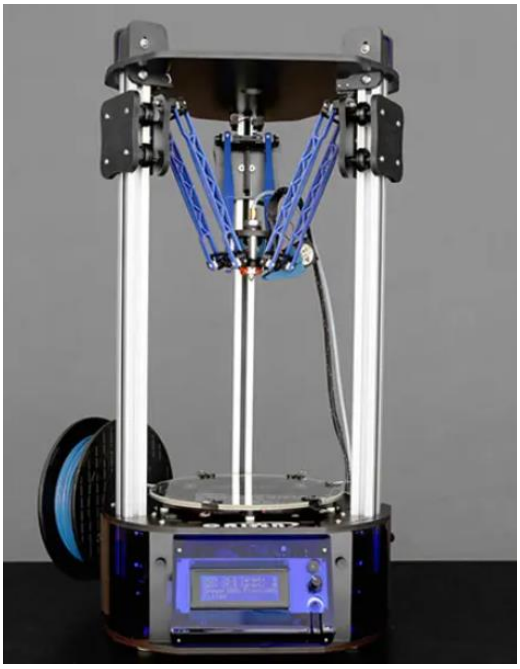


Figure 2-2 Delta frame

Compared with the models of other structures, the delta model has the characteristics of small size and simple structure. In terms of the size of the model, we can print the product larger. Because of its structural characteristics, this structure has fast printing speed and high transmission efficiency. The delta has the upper hand because of its parallel arms. Despite the small size of the delta, the printer must reserve space for the 3 parallel arms, which directly restricts the space utilization of the printer. In addition, because it uses a special interpolation algorithm for coordinate positioning, its printing accuracy is not high.

2.1.3 SCARA framework

SCARA is the abbreviation of Selective Compliance Articulated Robot Arm, which means Selective Flexible Articulated Robot Arm. The SCARA frame structure was originally used in industrial robots and assembly lines, but it is also widely adopted in 3D printers. It is a multi-articulated robotic arm that can control the height of the print head moving in the XY plane and in the Z-axis direction[23]。

As shown in Figure 2-3, the SCARA frame structure consists of two rotational joints and one translational joint. It is designed so that the printhead can be rotated within the horizontal plane, while the height in the Z-axis direction is controlled by translational joints. The print head moves up and down along the Z-axis, allowing for the printing of layers of different heights. At the same time, by controlling the rotation joint, the print head can move freely in the XY plane to draw objects of different shapes.

Figure 2-3 SCARA framework

One of the advantages of the SCARA frame construction is the fast and precise printing speed. The fast movement of the SCARA frame structure is excellent, and it can print high-precision, high-quality objects. In addition, the SCARA frame structure has a large working space and a high degree of flexibility, so it can be used to print objects of various shapes and sizes. However, there are some drawbacks to the SCARA framework structure. First of all, it is relatively complex and requires more parts and controllers, making it relatively difficult to maintain and repair. Secondly, the SCARA frame structure has a relatively small range of movement in the Z-axis direction and may not be able to print very tall objects. Finally, due to the need to move the printhead in the XY plane, there may be angular limitations that make it impossible to print complex 3D surfaces.

2.1.4 CoreXY framework

CoreXY is a common 3D printer frame structure that employs two independent belts with drive wheels to control the movement of the print head in the XY plane. Unlike other frame structures, the CoreXY frame structure does not require a panning frame to control the height in the Z-axis direction, so the volume and complexity of the printer can be reduced[24]。

As shown in Figure 2-4, in the CoreXY frame structure, two transmission wheels are located at both ends of the printer, and the print head is connected to these two transmission wheels through two transmission belts. The printhead can be moved in any direction within the XY plane, making the CoreXY frame structure ideal for printing large, complex 3D models.

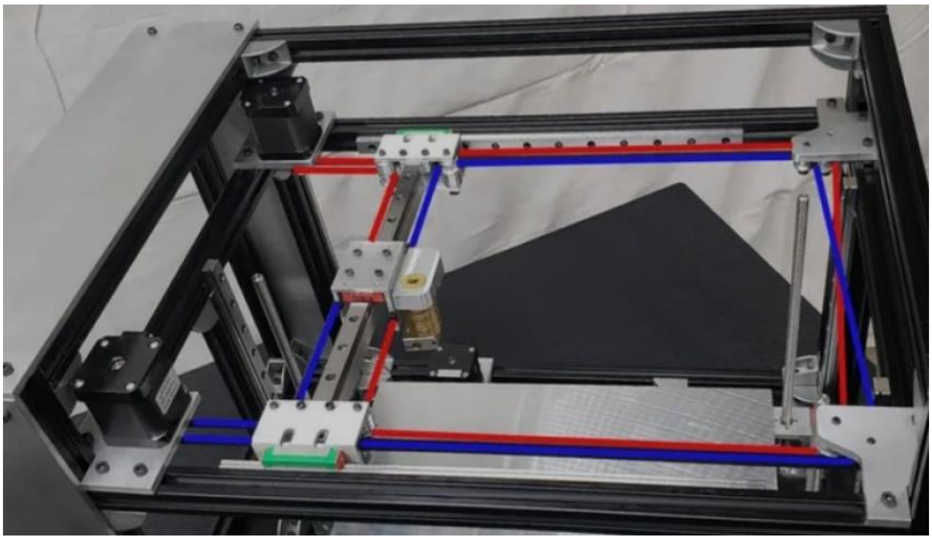


Figure 2-4 CoreXY framework

Compared with other frame structures, CoreXY frame structure has the following advantages: High-speed printing: CoreXY frame structure can achieve high-speed printing, because the print head only needs to move along the plane, not in the Z-axis direction, which can save time and energy. High precision: The CoreXY frame structure uses two independent drive belts for more accurate printing while reducing offset and twisting due to uneven tension. Large workspace: Since the print head of the CoreXY frame structure can be moved along the plane, it can be suitable for large 3D printers to print larger objects. High reliability: The mechanical structure of the CoreXY frame structure is very simple, which reduces the friction and wear of the mechanical parts, thereby improving the reliability and longevity[25]。

However, there are also some drawbacks to the CoreXY framework structure. First of all, the CoreXY frame structure is more complex and requires more parts and controllers, so it is relatively difficult to maintain and repair. Secondly, since the tension between the two belts needs to be precisely controlled, it can be somewhat challenging in terms of adjustment and calibration.

2.1.5 Frame design for embedded multi-material 3D printer

By comparing several common 3D printing frames,The embedded multi-material 3D printed frame uses a CoreXY structure. First of all, the design of the CoreXY frame can make the print head stable during movement, reducing the vibration and inertia of the movement, thereby improving the printing speed and accuracy. Since the printhead travels a very small distance during embedded 3D printing, it is important to ensure the accuracy of the print. Secondly, compared to other frames, the CoreXY frame has a simple design, easy to install and maintain, and its structure is stable and not prone to damage or wear, thus improving the reliability and longevity of the printer. Due to its relatively simple structure, it is easier to modify it to achieve more functions. Finally, the CoreXY frame is more compact and requires fewer parts, allowing for a greater range of motion in the same space while also reducing weight. This helps the printer to print on larger volumes of software devices[26]。

The principle of CoreXY is to control the movement of XY through two motors at the same time, when the left and right motors are in the same direction, move to the X axis, and when the two motors are reversed, move to the Y axis. The simultaneous action of two motors makes the force more stable than a single motor controlling one axis, and also reduces the weight of one motor on the XY stage. The same principle applies to the derived structures that follow.Kinematic principle and structure diagram of the CoreXY structure[27]See Figure 2-5, XThe relationship between the moving distance of the shaft and the Y-axis and the moving distance of the two motor belts is as follows:

$$\Delta X = \frac{1}{2}(\Delta A + \Delta B) \quad (2\text{-}1)$$

$$\Delta X = \frac{1}{2}(\Delta A - \Delta B) \quad (2\text{-}2)$$

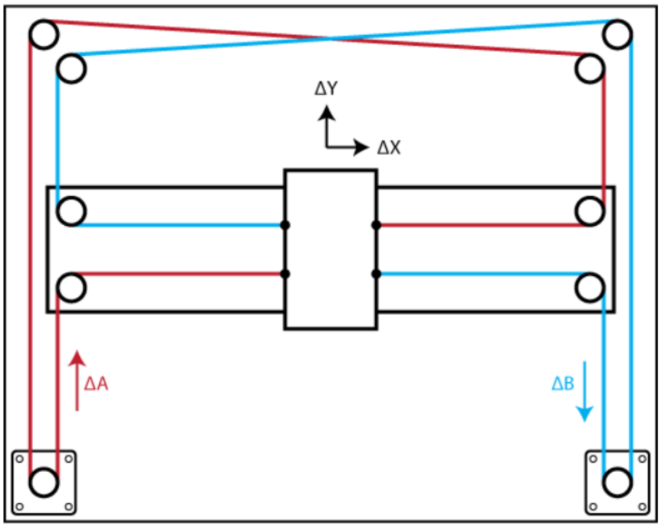


Figure 2-5 CoreXYSchematic diagram of the motion of the structure[27]

As shown in Figure 2-6, the main parts of the embedded multi-material 3D printer include a metal beam, a stepper motor, a screw rod, a transmission belt, a spool, and a hot bed. The overall frame adopts a metal beam as shown in Figure 2-7, and the advantage of this beam is that the necessary devices can be freely added to the frame. With nuts, screws and spacers, the unit can be fixed to the frame, which facilitates the installation of the sprinkler changer.

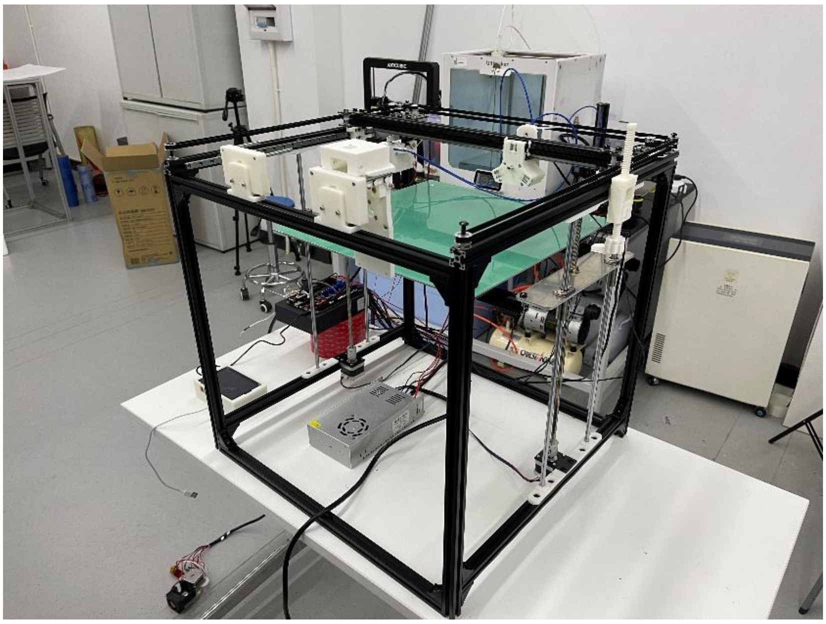


Figure 2-6 Appearance of the 3D printer

Figure 2-7 Metal beam

2.2 Sprinkler replacement device design

The key to the design of multi-material 3D printers is how to change the printing material during the printing process. Manual replacement of multi-material 3D printers requires the design of an efficient and reliable material replacement system, including material supply, material switching, material mixing, etc. This needs to take into account the characteristics, adhesion, temperature requirements and other factors of different materials to ensure that the material replacement process will not cause problems such as material blockage, leakage, and confusion, so as to ensure the stability and reliability of the printing process. Multi-material 3D printers usually use several methods to switch materials: combined multi-jet, single-nozzle multi-extrusion outlet, liquid material for material, and printhead for switching[28]。

2.2.1 Combined multi-nozzle method

The combined multi-jet method is a common material exchange method for multi-material 3D printers. See Figure 2-8， In this method, the 3D printing head is equipped with multiple independent printheads, each for a different material.[28]These printheads can work at the same time, spraying different materials separately, allowing for simultaneous printing of multiple materials. The working principle of the multi-nozzle method is to switch between different materials by controlling the switching state of different nozzles. When it is time to switch materials, the control system shuts down the printheads that are currently in use and turns on the printheads that need to be switched. In this way, different materials can be sprayed onto the print platform from different printheads, enabling multi-material printing.

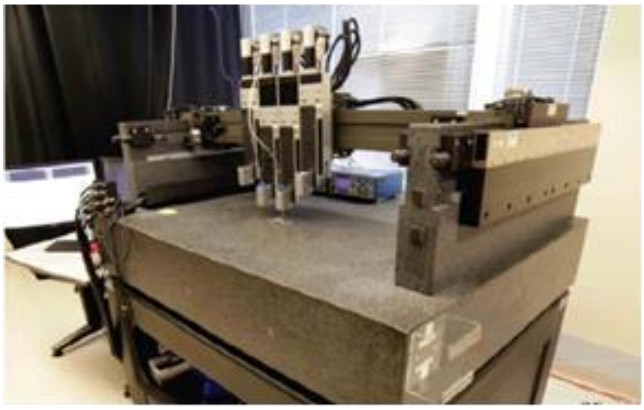


Figure 2-8 MultiJet 3D Printer[28]

The advantage of the combined multiJet method is that multiple materials can be used at the same time, enabling complex multi-material printing. For example, you can use different colors of materials in the same printed object, or different parts of the same object with different properties, such as materials with different hardness, transparent and opaque materials, etc., to achieve richer and more diverse printing effects[29]。

2.2.2 Single nozzle multi-extrusion outlet method

The single-printhead multi-extrusion outlet method is another common material exchang e method for multi-material 3D printers[30]。 In this method, only one printhead is mounted o n the 3D printing head, but there are multiple extrusion outlets inside the printhead, each of w hich is used for a different material. On different extrusion outlets, different switches can be c ontrolled to control the corresponding materials according to the needs to achieve the purpose of multi-material printing.

The working principle of the single nozzle multi-extrusion outlet method is to switch bet ween different materials by controlling the switching state of different extrusion outlets. Whe n it is time to switch materials, the control system closes the extrusion outlet that is currently i n use and opens the extrusion outlet that needs to be switched. In this way, different materials can be extruded from different extrusion ports onto the printing platform, thus enabling multi-material printing.

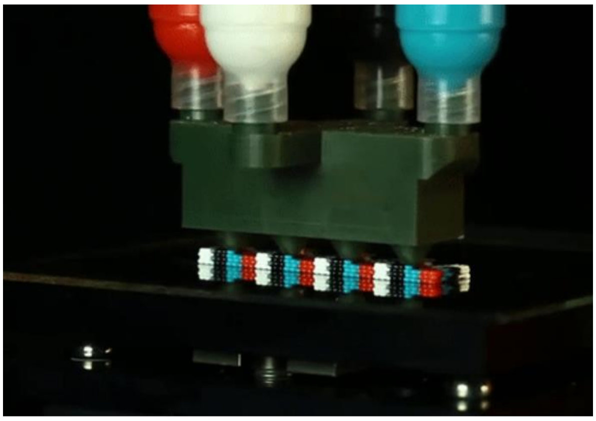


Figure 2-9 MultiJet 3D Printer[30]

The advantage of the single-nozzle multi-extrusion outlet method is that it is relatively si mple in mechanical structure, only one nozzle is needed, and no additional nozzle installation and commissioning are required. At the same time, since there is only one printhead, there wil l be no position errors between different printheads or material mixing problems during the pr inting process.

2.2.3 Liquid material-for-material method

The liquid material exchange method is a relatively novel material exchange method for multi-material 3D printers. In this way, the printhead achieves multi-material printing by mixing different liquid materials. This method often requires a dedicated liquid nozzle and mixing system to control the mixing ratio and jet velocity of different liquid materials. The liquid material-to-material method works by controlling the jet speed and mixing ratio of the liquid nozzle to achieve the switching of different materials. When it is necessary to switch materials, the control system adjusts the working parameters of the liquid nozzle, thereby changing the mixing ratio and jetting speed of the liquid material, so as to achieve multi-material printing[31]。

The advantage of the liquid material exchange method is that it allows for very detailed multi-material mixing, resulting in more detailed and complex printing results. For example, you can achieve a smooth gradient effect with different colors in the same printed object, or use different materials with different properties, such as soft and hard materials, in different parts of the same object, for more advanced and complex printing applications.

2.2.4 Change the sprinkler method

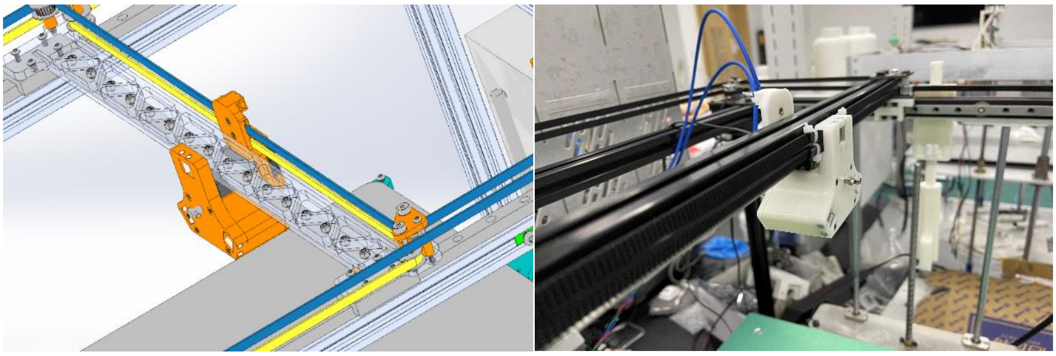
The basic principle of multi-material 3D printers is to switch printing materials by changing the printhead. In general, each printhead can only print one material, so it is necessary to change different printheads as needed to achieve multi-material printing. Printhead change methodMulti-material 3D printers usually use multiple independent printheads, each printhead corresponds to a material. During the printing process, the output of different materials can be controlled by controlling the working status of different printheads. In general, each printhead has an independent control circuit, and the switching status of the printhead can be controlled by software or hardware[32]。

The main advantage of multi-material 3D printers is that they are simple and reliable. Since each printhead is responsible for only one material, different materials do not interfere with each other, and high accuracy and stability can be achieved. At the same time, because each printhead can be controlled individually, it can flexibly control the change of printing materials to achieve complex printing needs.

2.2.5 Design of printhead changer for embedded multi-material 3D printer

By comparing several common material replacement methods, embedded multi-material 3D printers use the method of changing printheads for material switching. The device mainly consists of a locking device and a power transmission device[33]。

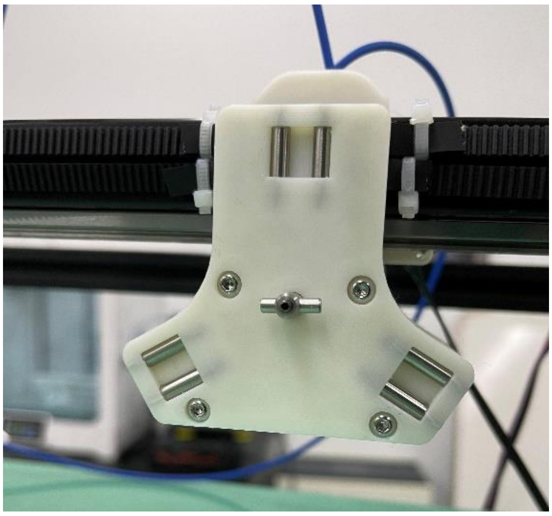
As shown in Figure 2-10, the locking device is fixed on the slider of the frame XY cross rail, which is divided into the front, middle and rear parts.



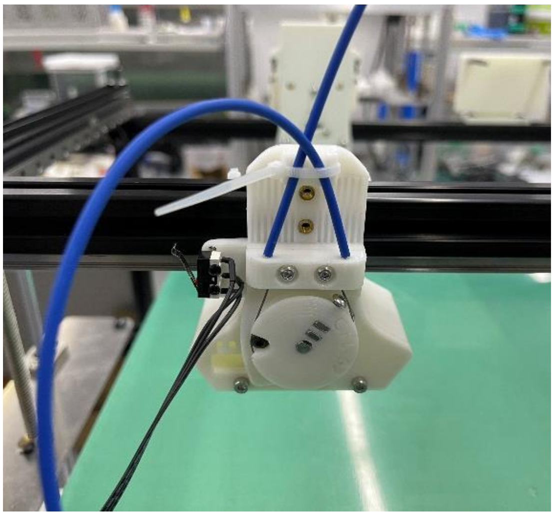
a)Structural diagram[33] b)Physical drawing

Figure 2-10 Locking device

The front part is the joint between the locking device and the nozzle, and an iron pin protrudes from the front part to fix it with the nozzle. It is equipped with three positioning devices. Each positioning device consists of a groove and two positioning pins. The positioning device improves the tolerance rate during docking and makes it easier to attach the locking device to the upper sprinkler. The function of the middle part is to fix the locking device on the slide and connect the front and rear. The rear part is connected with the power transmission device, and the rotation of the iron pin is controlled by rotating the disc to realize the locking and unlocking of the sprinkler head. The rear disc is equipped with a limit switch, and when the tool is picked up, the twist lock will rotate into the slider to reach the specified set point, at which point the tool is considered locked. However, this setpoint is not position-based, but torque-based. That is, the tool is considered fully engaged only when a specific torque value is applied to the twistlock. Torque-based locking systems offer key advantages[33]。 First of all, the system is not prone to wear and tear. As the machine cycles through thousands of lock/unlock movements, the twist-lock pin or wedge plate will eventually wear out. With torque-based locking settings, the tool will continue to lock consistently throughout the life of the part, rather than gradually reducing reliability. Second, this setup makes the printer more willing to adapt to subtle changes in geometry on the wedge plate feature. Even if the wedge plates are slightly different from the manufacturing process, they may still be effective[33]。



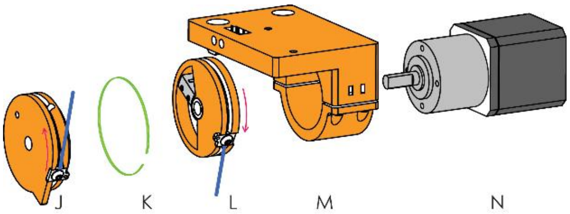
a)Front



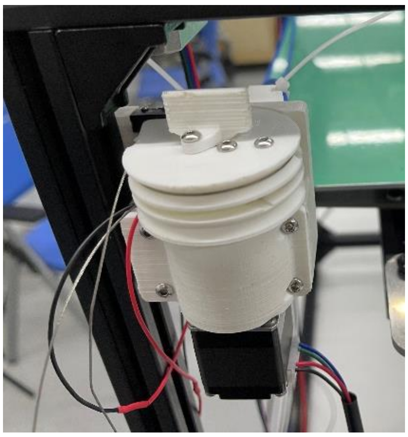
b) Rear

Figure 2-11 The front and rear parts of the locking device

The power transmission is shown in Figure 2-12, the twist lock is driven by a fixed motor that drives two flexible mechanical control cables that control the pulleys. These control cables are sheathed in extended springs called spring guides, allowing them to follow the slider freely. These control cables work similarly to bicycle brake cables[33]。 Pulling a control cable rotates the twistlock into the wedge, locking the tool. Pulling the other cable releases the twistlock from the wedge, which in turn releases the tool. The two cable ends are connected to a motor that is fixed to the frame. With the remote cable, we can move the drive motor away from the carriage, reducing the weight of the carriage and thus increasing the weight budget of the tool[33]。



a)Structural diagram[33]



b)Physical drawing

Figure 2-12 Power transmission device

In any special case, a rotating motor triggers a limit switch to detect a locked/unlocked tool. When one limit switch is stationary, another limit switch floats on a freewheeling pulley that is connected to another pulley fixed to the shaft by an extension spring[33]。 This setup forms a tandem elastomeric actuator, a robot-inspired sensing torque setting[34], the principle of which is determined by Equation 2-3, Equation 2-4 and Figure 2-13[34]。 where is the known coefficient of elasticity of the springs, and the elongation of the two springs, respectively. In this way, the transmitted force is linked to the amount of spring expansion.$K X_1 X_2$

$$X = X_1 - X_2 \tag{2-3}$$

$$F = K * X \tag{2-4}$$

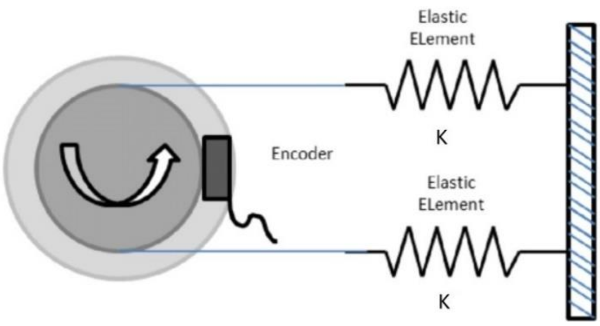
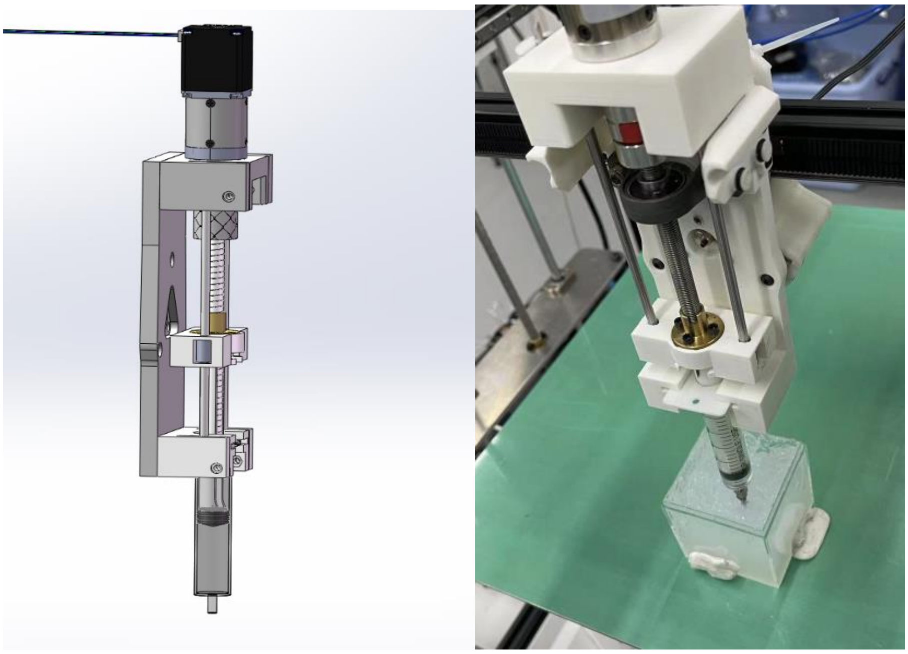


Figure 2-13 Schematic diagram of a series elastic actuator

During the tool locking process, the twist lock is rotated onto the wedge plate until it "jams", leaving the cable in tension. As the motor continues to rotate, this tension increases and the extension spring begins to stretch. Eventually, the spring is sufficiently stretched, and once the spring is stretched, it triggers another limit switch that is set at a specific position within the motor's range of motion. Since the force of an ideal spring is directly proportional to its tensile force, and this force is exerted on the moment arm around the pulley, this translates into a fixed torque value, at which point the tool is considered locked[33]。

2.3 Printhead design

The nozzle has two main functions, one is to fix the syringe and push the syringe, and the other is to be able to dock with the nozzle locking device. The overall structure of the printhead is shown in Figure 2-14The motor pushes the syringe by driving the screw to rotate and realize the extrusion of the material. Linear guide rails on both sides ensure that the middle slide moves perpendicular to the syringe to ensure accuracy. The outer structure of the nozzle is provided with a keyhole connected with the nozzle locking device, and the iron ball with triangular distribution is docked with the positioning device on the nozzle locking device, so as to improve the docking accuracy[35]。 This design is called Maxwell couplings[33], which is a mechanical design pattern used to fully constrain two entities with six points of contact. In an ideal world, two entities are joined together and are infinitesimal dots. This principle exerts high stresses on a small surface area, so rigid materials such as steel are used in practice to form coupling points.



a)Structural diagram b) Physical drawing

Figure 2-14 Printhead structure

2.4 Sprinkler docking station design

The nozzle docking station is the position where the nozzle stops when it is not in use, as shown in Figure 2-15The two positioning pins protruding from the docking station are used to hold the sprinkler head. The unit is height-adjustable for easy commissioning during later installation[33]。

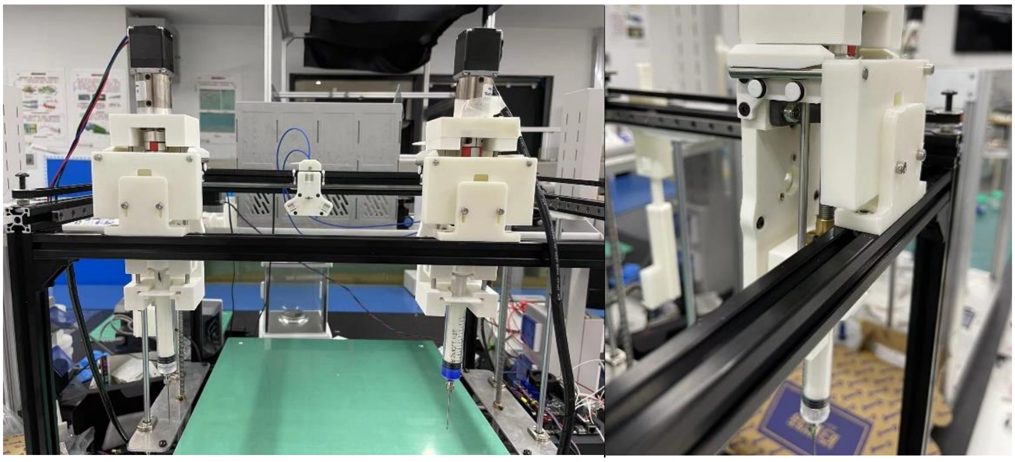


Figure 2-15 Structure of the sprinkler docking station

2.5 Z-axis zero positioner

Since embedded 3D printing is carried out in containers, and the containers printed each time are not necessarily the same, this results in a different Z-axis zero point for each print. Therefore, a Z-axis zero positioner is designed to adjust the position of the Z-axis limit switch. By turning the nut, the screw rod moves up and down to adjust the height of the limit switch.

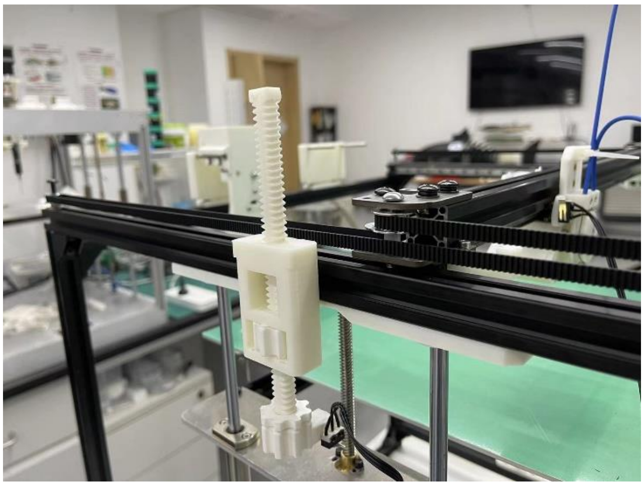


Figure 2-16 Z-axis zero positioner structure

2.6 Summary of this chapter

This chapter introduces the mechanical structure of an embedded multi-material 3D printing system. Firstly, several common frames of Cartesian, Delta, SCARA, and CoreXY were introduced, and CoreXY was finally selected as the frame structure of the printing system to improve the printing speed and accuracy[25]。 The main parts of the frame include metal beams, stepper motors, screw rods, transmission belts, spools, and heat beds. Secondly, four nozzle replacement strategies were introduced, namely, the combined multi-nozzle method, theSingle nozzle multi-extrusion outlet method、Liquid material change method and nozzle change method. In the end, the project chose to change the nozzle for material switching. The sprinkler head changer device is composed of a locking device and a power unit, which converts the fixed torque and completes the locking and unlocking of the sprinkler by using the principle of series elastic actuators[33]。 Then, the design of the integrated nozzle was introduced, and the design of the Maxwell coupling was used to realize the docking of the nozzle and the locking device. Finally, the nozzle docking station and Z-axis zero locator of the 3D printing system were introduced, which were used to dock the nozzle and dynamically adjust the Z-axis direction zero point, respectively. Through the design of the mechanical structure, the 3D printing system has the hardware foundation for embedded multi-material 3D printing.

Control system design for embedded multi-material 3D printing system

3.1 Firmware for 3D printing systems

The firmware of a 3D printer is an embedded software that is mainly used to control various actions and behaviors of the 3D printer, such as moving, heating, cooling, reading sensor data, etc[36]。 It runs directly on the 3D printer's main control board and is responsible for interacting and communicating with other hardware components[37]。 Firmware is the key to the proper functioning of 3D printers. Common 3D printing firmware includes Marlin,Repetier、Smoothie、Clipper[38]。

3.1.1 Marlin firmware

Marlin is a widely used open-source 3D printer firmware that supports a wide range of SBCs and controllers and is capable of running on a variety of different 3D printers[39]。 Marlin's primary goal is to provide a 3D printing experience that is high-quality, stable, and customizable[40]。

Marlin supports a wide range of controllers and single board computers, such as Arduino, RAMPS, MK3, etc. These controllers and single board computers are widely available and are relatively inexpensive and easy to obtain. As a result, users can choose the right controller and single board computer according to their needs, and the Marlin firmware is highly compatible and can run on different hardware platforms. The Marlin firmware has a number of useful features, including: automatic platform calibration, power failure, temperature protection, multiple sensor support, warm-up and cool-down functionsMultiple extrusion head support, voice prompts, and more.

3.1.2 Repetier firmware

Repetier is a modular 3D printer firmware that can be plugged in, supporting multiple extruders and automatic bed flatness calibration. Repetier supports user-defined G-code commands and macros, which allows users to implement more automated operations[41]。

Repetier also provides a real-time control panel through which users can adjust parameters such as print speed, temperature, etc., without the need to restart the printer. In addition, Repetier supports a multi-language interface, allowing users to operate in the language they are comfortable with.

The downside of Repetier is that due to its modular design, its code can be complex, leading to some performance bottlenecks. In addition, the configuration of Repetier requires some programming knowledge, which can be difficult for novices.

3.1.3 Klipper firmware

Klipper is a 3D printer firmware developed by Kevin O'Connor that comes with a number of unique features and benefits. Unlike traditional firmware, Klipper runs on the host computer, not on the controller board. This means that Klipper can take full advantage of the processing power of the host computer, which can improve the performance of the printer[42]。

Klipper has several striking features: First, high-precision stepper motion. Klipper uses an application processor, such as a low-cost Raspberry Pi, to calculate printer motion. The application processor decides when to step each stepper motor, compresses these events, and sends them to the microcontroller. The microprocessor will execute each event at the requested time. Each step event is scheduled with an accuracy of 25 milliseconds or more. Klipper does not use motion estimation, such as Bresenham's algorithm, but instead calculates accurate step times through acceleration and mechanical motion physics. More precise stepper motor movement means quieter and more stable operation of the printer. Second, Klipper supports printers with multiple microcontrollers. For example, one microcontroller can be used to control the extruder, another to control the heater, and a third to control the other printer components. The Klipper host program implements clock synchronization, which solves the clock drift between microprocessors. Enabling multiple controllers only requires adding a few lines to the configuration file and does not require any special code.

3.1.4 Smoothie Firmare

Smoothie is an ARM microprocessor-based 3D printer firmware that supports multiple extruders and automatic bed flatness calibration. Smoothie's code is clearly structured and easy to configure, allowing users to personalize it by modifying the configuration file. In addition, Smoothie offers some useful features such as temperature control, stepper driver protection, smooth motion, and more.

The advantage of Smoothie is that it has a flexible design that can adapt to different printer structures and components. In addition, the configuration of the smoothie is relatively simple, making it easy for novices to get started. But the downside of it is that Smoothie can run slower compared to other firmware.

3.2 Firmware selection and control system design for embedded multi-material 3D printing system

Klipper was chosen for the firmware of this 3D printing system based on its following advantages:

1. Higher printing speed and accuracy: Klipper offloads most of the computation to the computer, allowing the firmware to focus only on simple motion commands. This can greatly improve the speed and accuracy of printing.
2. Easier configuration and debugging: Klipper's configuration files are written in Python and can be modified with a simple text editor, making configuration more flexible and convenient. In addition, Klipper provides a wealth of debugging information to help you quickly troubleshoot problems.
3. Support for multiple hardware platforms: Klipper can run on multiple hardware platforms, including Raspberry Pi, BeagleBone, and more, so you can upgrade your older printer to a more powerful device.
4. Plug-in architecture: Klipper has a plug-in architecture that allows you to extend functionality by installing plugins. For example, users can install the OctoPrint plug-in for remote monitoring and control.

In this control system, the upper computer uses a Raspberry Pi 4 Model B Rev 1.1, the processor is ARMv7 Processor rev 3 (v7l), and the lower computer uses a 3D printer motherboard, BIGTREETECH Octopus Pro. The circuit diagram of the printing system is shown in Figure 3-1. The advantage of using Raspberry Pi in the upper computer lies in its efficient computing power: compared to embedded devices, Raspberry Pi's processor and memory are more powerful. This means that the Raspberry Pi can handle printing tasks faster and has better multitasking capabilities. At the same time, the Raspberry Pi can also increase the speed of operation by overclocking and other methods. The 3D printer motherboard BIGTREETECH Octopus Pro can be used as a Klipper lower computer, which can greatly improve the running speed: The BIGTREETECH Octopus Pro motherboard uses eight independent TMC5160 stepper motor driver chips, each driver has an SPI interface, and the communication speed with the main control chip is faster, which can better support Klipper's high-speed motion control algorithm, and improve the printing speed and printing quality. In addition, the motherboard adopts the XMC1400 series of 32-bit main control chips, with rich peripheral interfaces and powerful expansion capabilities, which can more flexibly meet the different needs of users, such as supporting more sensors and expansion modules.

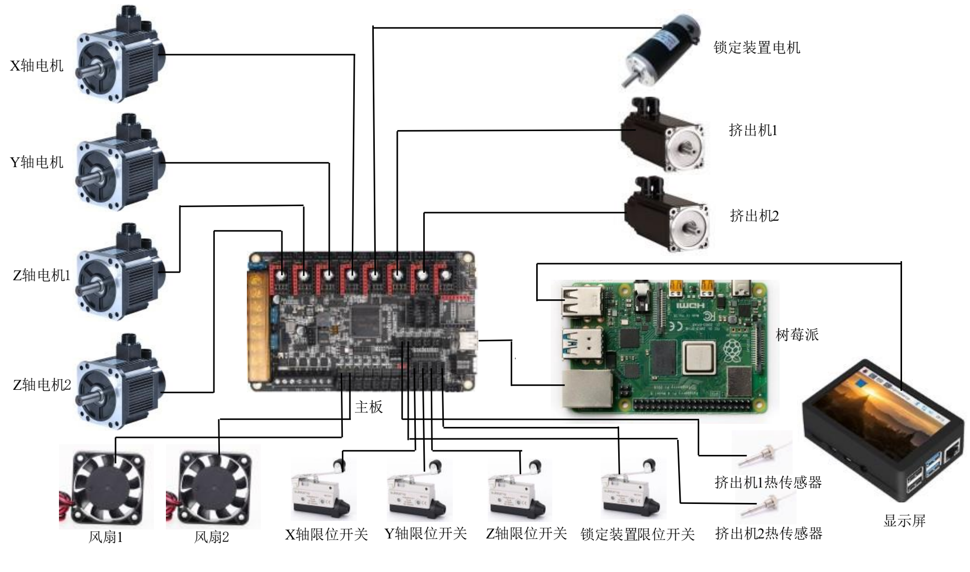


Figure 3-1 Printing system circuit diagram

3.3 programming

The goal of this program is to enable people to build a very capable and advanced multi-material printhead 3D printer using Klipper firmware. The main profiles include the main profile, the tool-lock profile, and the pick-and-place profile[43]。

The main profile configures information such as the X, Y, and Z axes of the stepper motor, the control pins of the manual stepper motor, the limit switch position, the maximum range of movement, and the speed when returning to the origin. The specific values of these parameters can be adjusted as needed to meet different printing needs. In addition, the printing tool is automatically returned to its position when the printer is initialized. If a tool is currently in use, the user is prompted to manually return it to the starting position. This can help ensure the correct operation of the printer and improve print quality and efficiency. In the main profile, the location of the sprinkler head is also defined.

```
[gcode_macro T0]
gcode:
        TOOL_PICKUP ZONE_X=50 ZONE_Y=250 PARK_X=50 PARK_Y=270 OFFSET_X=5 OFFSET_Y=5 OFFSET_Z=0
        ACTIVATE_EXTRUDER EXTRUDER=extruder

[gcode_macro T1]
gcode:
        TOOL_PICKUP ZONE_X=250 ZONE_Y=250 PARK_X=250 PARK_Y=270 OFFSET_X=2 OFFSET_Y=2 OFFSET_Z=0
        ACTIVATE_EXTRUDER EXTRUDER=extruder1
```

Figure 3-2 Definition of nozzle docking location

The Tool Lock profile defines a manual stepper that controls the printer's Tool Lock. The LOCK_INIT macro defines the lock state variable[43]and set its initial value to True. The TOOL_LOCK macro locks the tool and sets the lock state variable to True. The TOOL_UNLOCK macro unlocks the tool and sets the lock state variable to False. When performing an unlock operation, the macro saves the current state, then moves the manual stepper motor to the unlock position, unlocks the tool, and then resumes the state. When performing a lock operation, the macro also saves the current state, then moves the manual stepper motor to the lock position, locks the tool, and then resumes the state. Because the lock state variable needs to be checked before unlocking or locking, the LOCK_INIT macro also defines the variable_lock_state variable and updates the value of this variable after the lock or unlock operation is performed. Figure 3-3 shows the code for TOOL_LOCK and TOOL_UNLOCK.

```
[gcode_macro TOOL_UNLOCK]
gcode:
        {% if printer["gcode_macro LOCK_INIT"].lock_state %}
        SAVE_GCODE_STATE NAME=tool_lock_state
        MANUAL_STEPPER STEPPER=tool_lock SET_POSITION=100
        MANUAL_STEPPER STEPPER=tool_lock Move=90 SPEED=10 STOP_ON_ENDSTOP=-1
        MANUAL_STEPPER STEPPER=tool_lock Move=0 SPEED=50 STOP_ON_ENDSTOP=1
        MANUAL_STEPPER STEPPER=tool_lock SET_POSITION=0
        SET_GCODE_VARIABLE MACRO=LOCK_INIT VARIABLE=lock_state VALUE=False
        RESTORE_GCODE_STATE NAME=tool_lock_state
        {% endif %}

[gcode_macro TOOL_LOCK]
gcode:
        {% if not printer["gcode_macro LOCK_INIT"].lock_state %}
        SAVE_GCODE_STATE NAME=tool_unlock_state
        MANUAL_STEPPER STEPPER=tool_lock SET_POSITION=0
        MANUAL_STEPPER STEPPER=tool_lock Move=10 SPEED=10 STOP_ON_ENDSTOP=-1
        MANUAL_STEPPER STEPPER=tool_lock Move=100 SPEED=50 STOP_ON_ENDSTOP=1
        MANUAL_STEPPER STEPPER=tool_lock SET_POSITION=100
        SET_GCODE_VARIABLE MACRO=LOCK_INIT VARIABLE=lock_state VALUE=True
        RESTORE_GCODE_STATE NAME=tool_unlock_state
        {% endif %}
```

Figure 3-3 Locking and unlocking codes of the tool

The Pick & Place profile defines the process of picking and returning the sprinkler, also known as the TOOL_PICKUP and TOOL_DROPOFF[43]。TOOL_PICKUP macro definition is used to pick up the sprinkler head from the docked location and move it to the specified location. It uses several default parameters called ZONE_X, ZONE_Y, PARK_X, PARK_Y, and so on, which specify where the sprinkler head is parked and docked, as well as how much the sprinkler head is offset. The implementation of this macro involves several steps, including:

1. Save the current gcode state.
2. Get the current location and homing location, if no homing location is set, use the current location as the homing location.
3. Lower the Z-axis by 100mm.
4. If there is a sprinkler at present, put the sprinkler down; Otherwise, if it is locked, it is unlocked.
5. Move the locking device to the parking area.
6. Dock the locking device at the designated location.
7. Lock the sprinkler.
8. Move the sprinkler head to the specified position.
9. Save the location information of the sprinkler head and parking area.
10. Marker printhead present.

11. Move the sprinkler back to its position.

12. Restore the previously saved gcode state.

13. Set the printhead offset.

TOOL_DROPOFF's gcode macro to remove the tool from the printer. It first checks if the tool_present variable in the DOCK_INIT macro is true to ensure that a tool exists before removing it. If a tool exists, the macro does the following:

1. Set the offset to 0 to ensure that no offset is used when moving.
2. Move the locking device to the sprinkler area.
3. Dock the sprinkler head at the designated location.
4. Unlock the sprinkler.
5. Move the locking device back to the tool area.
6. Set the tool_present variable to False, indicating that the sprinkler head has been removed.

Finally, the macro restores the previously saved state, including information such as position, temperature, and extruder motor position, and sets the offset to 0 to ensure that subsequent operations are not affected.

3.4 Summary of this chapter

This chapter introduces the design of a control system for an embedded multi-material 3D printing system. First, several common 3D printing firmware are introduced, namely Marlin, Repetier, Smoothie, and Klipper[38]。 Klipper was selected as the firmware for the 3D printing system, based on its higher printing speed and accuracy. Secondly, the circuit system of the system is introduced, using the Raspberry Pi as the upper computer and the 3D printed motherboard as the lower computer, which improves the computing power, multitasking ability and memory. Finally, the configuration file and program design of the 3D printing system are introduced, and the code logic of the printhead change process is emphatically introduced. Through the design of the control system, the 3D printing system has a software basis for embedded multi-material 3D printing.

Preparation of soft materials for embedded multi-material 3D printing

4.1 Soft material molding mechanism and process flow of embedded 3D printing

4.1.1 Additive molding mechanism of vulcanized silica gel at room temperature

Room Temperature Vulcanizing Silicone Rubber (RTV Silicone) is a special type of silicone rubber characterized by a vulcanization reaction that cures into an elastic material at room temperature. It is composed of polymers and crosslinkers, etc., and has excellent heat resistance, weather resistance, and chemical stability. Its main component is siloxane, which can be cross-linked at room temperature without heating or pressure by homogeneously mixing with different types and contents of crosslinkers, vulcanizing agents, fillers, etc[44], thus forming an elastomer. RTV silicone is mainly divided into two types: condensation type and additive molding. Condensed RTV silica gel is based on silicone monomers or polymers containing hydrolyzable groups, and reacts with compounds containing hydroxyl or alcohol groups to produce hydrolysis products, which are formed into three-dimensional cross-linked structures through polycondensation reaction and cured into silicone rubber. Additive RTV silica gel is based on a polymer containing reactive groups, and an addition reaction occurs with a compound containing hydrogen groups to form a three-dimensional cross-linked structure and solidify into silicone rubber. Compared with the condensed type, the addition silica gel does not produce by-products during the vulcanization process, has a very low shrinkage rate, uses less catalyst, and is easy to control the crosslinking density and vulcanization speed, and can achieve deep vulcanization at room temperature.

Addition molding silica gel is generally divided into two parts of AB mixed use, also known as two-component addition RTV silica gel, which usually uses polysiloxane containing vinyl (-CH=CH2) as the base polymer, and polysiloxane containing silicon-hydrogen bond (Si-H) as the crosslinking agent, and the silicon hydrogenation addition reaction occurs under the action of platinum catalyst, and finally forms an elastomer with a three-dimensional cross-networked structure[45], and its reaction formula is shown in Figure 4-1.

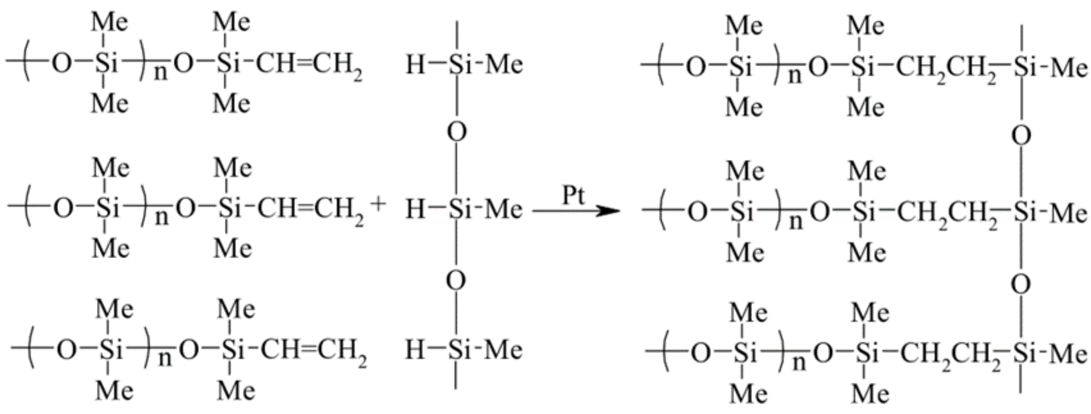


Figure 4-1 Vulcanization mechanism of two-component additive RTV silica gel[46]

Additive RTV silicone rubber is usually composed of vinyl silicone oil, hydrogen silicone oil, platinum catalyst at the sealing end (or side base), and corresponding fillers, additives, inhibitors, etc. can be added as needed to meet the requirements of mechanical, optical or electrical properties. The content of different components has an important impact on the properties of the silica gel structure. As a base polymer, vinyl silicone fluids have a lower ethylene content, the greater their fluid viscosity. When the ethylene content is too low, the cross-linking density is small, the performance of the vulcanized rubber is poor, and the tear strength is low; When the ethylene content is too high, the cross-linking points increase, the cross-linking density is larger, the vulcanized rubber becomes hard and brittle, and the elongation is low. As a crosslinker, the hydrogen atoms of the Si-H bonds on the hydrosilicone oil are activated by a catalyst and then additionally react with ethylene to form a crosslinking network. The molar ratio of silica hydrosilane Si-H and silicene Si-vi in the silica gel components has a great influence on the properties of silica gel. When the silicon-hydrogen ratio is less than 1, the silica gel is not completely vulcanized, resulting in a viscous structure. When the silicon-hydrogen ratio is increased to an appropriate range, the silica gel can be completely and uniformly vulcanized to obtain better mechanical properties; However, an excess of hydrosilicone oil can lead to a decrease in performance$n_{SiH}:n_{SiVi}$[47]。Considering the full utilization of ethylene and the loss of silicon-hydrogen bonds, the hydrogen group is usually appropriately increased in practical applications, that is, the silicon-hydrogen ratio should be greater than 1[48]。 In addition to the base polymer and crosslinker, fumed silica as a filler can enhance the mechanical properties of silica gel, but also change the rheology and permeability of the polymer, thereby greatly increasing the viscosity of the fluid and imparting plastic deformation and yield stress. In contrast, the right amount of vinyl MQ silicone fluid can significantly improve the mechanical properties of silica gel with little effect on rheology and transparency. As a reaction condition, the amount of platinum catalyst used affects the curing rate of silica gel. Due to its high catalytic activity, the requirement for platinum in the reaction is very low, at least 0.1 ppm of the total polymer[48]。

4.1.2 Process design

In the silica gel casting molding process, silica-based polymers, crosslinkers, catalysts, and fillers are homogeneously mixed, and cross-linking reactions and curing occur at room temperature or after heating. Due to the high catalytic efficiency of platinum catalysts, a small amount of platinum catalysts can trigger the curing reaction of the polymer in a certain area. Assuming a 3D printing system, the catalyst units are distributed in the material system small and uniform enough to form a homogeneously cured silica gel structure like all materials are homogeneously mixed. Based on this principle, the silica gel printing method used in this project is to continuously and uniformly extrude the diluted catalyst ink into a support matrix containing a silica gel polymer. When the printer moves according to a certain path and extrudes the ink, the material contacts and fuses, and then the matrix is locally cross-linked and solidified to form the corresponding silica gel soft structure. Since the catalyst activates the hydrogen atoms on the hydrogen-containing silicone oil[46], so the catalyst needs to be used separately from the crosslinker, using a low-viscosity vinyl silicone oil as a diluent to participate in the crosslinking reaction after extrusion. In addition, due to the rheological properties of the support matrix required for embedded 3D printing, in addition to the base polymer and crosslinker, the matrix includes fumed silica powder for rheological modification, and vinyl MQ silicone for mechanical modification (optional). Similar to commercially available two-component RTV silica gels, the materials used in this printing process are divided into catalyst components and matrix components. By enabling a print-on-demand curing process that separates the catalyst from the crosslinker, the limitation of the material's operating time is eliminated.

In the manufacture of flexible sensors, carbon nanotubes in carbon-based nanomaterials have the characteristics of one-dimensional cylindrical hollow structure, high aspect ratio, and material contact to form a tight conductive network, which has the characteristics of high conductivity, high strength, high stiffness, and soft and bendable. Combined with flexible substrates, composite materials with good mechanical properties and stable electrochemical properties can be formed. Based on the piezoresistive effect, composites made of carbon nanotubes can convert structural deformation into changes in resistance values, which have been widely used in flexible sensors and wearable devices[[49]-[51]]。 Therefore, in order to further expand the function of silica gel structures, low-cost and high-availability multi-walled carbon nanotubes (MWCNTs) are used as fillers for conductive inks, and multi-material printing technology is used to realize the integrated manufacturing process of soft robots with sensing functions. For multi-material printing, the process is to divide the design structure into multiple parts for slicing and generating multiple G-code programs; When a part of the code is printed, change the printing ink and continue to print the next program; Do the same post-print processing until all programs have been printed.

4.2 Preparation of soft materials for embedded 3D printing

4.2.1 Experimental raw materials

Table 4-1 shows the experimental raw materials, specifications and manufacturers used in 3D printing in this project.

Table 4-1 Experimental raw materials

name	specification	Manufacturer
Vinyl silicone oil MP5000	Vinyl content: 0.16 wt%, Viscosity 5000 mPa•s	Shanghai Sibao High-tech Materials Co., Ltd
Hydrogenated silicone oil MH180	Hydrogen content 0.18 wt%, Viscosity 50 mPa•s	Shanghai Sibao High-tech Materials Co., Ltd
Vinyl MQ Silicone DT2750	M/Q = ~0.9, Vinyl content1.4 wt% Viscosity 7000 mPa•s	Guangzhou Delta Silicone Technology Co., Ltd
Fumed silica A380	The specific surface area is 380 m2/g	Evonik, Germany

Vinyl silicone oil MP450	Vinyl content 043 wt %、Viscosity 450 mPa•s	Shanghai Sibao High-tech Materials Co., Ltd
Platinum catalyst	1000 ppm	Shanghai Sibao High-tech Materials Co., Ltd
High-purity multi-walled carbon nanotubes	Pipe diameter 3-15 nm, Pipe Length 15-30 μm	Guangdong Kaisa New Materials Co., Ltd
No. 120 solvent oil	—	Wentian Environmental Protection Technology Cleaning Agent Co., Ltd

4.2.2 Preparation of catalyst inks

Catalyst inks for silicone printing contain platinum catalysts and low-viscosity vinyl silicone oil MP450. In this paper, the material concentration of the catalyst ink used in the experiment was kept unchanged, that is, the two materials were added to the container at a mass ratio of 1:125, and the electric stirrer was used to stir evenly at a speed of 1000 rpm for 5 minutes. In addition, there is the option to add a small amount of pigment or phosphor for mixing to enhance the visualization of the print path. Once stirred, the ink can be filled into the syringe after standing or vacuuming.

4.2.3 Preparation of conductive inks

In order to prepare conductive inks for printing flexible sensors, platinum catalyst and MP450 were used as raw materials with a mass ratio of 1:250, stirred and mixed at a speed of 1000 rpm for 5 minutes, then about 4.9wt% MWCNT was added, and stirred at 2400 rpm for more than 5 minutes in a vacuum defoaming mixer to make the filler evenly mixed, thus imparting the characteristics of conductance and shear thinning of the extruded ink. Finally, the ink is loaded into a syringe and the air bubbles are extruded.

4.2.4 Preparation of support matrix

Since the silicon-hydrogen ratio in the material and the concentration of MQ silicon affect the mechanical properties of the print, the mass of each component needs to be determined and calculated as needed before the support substrate is prepared. If and denote the mass of MP5000, DT2750, MH180, and A380, respectively, then the mass of the support matrix is

$$W = W_1 + W_2 + W_3 + W_4 \quad (4\text{-}1)$$

First, given the mass of MP5000, the mass fraction of DT2750 in the matrix liquid material, the mass fraction of A380 in the entire matrix material, the silicon-hydrogen ratio (A) of the entire material system (including the matrix and catalyst ink), and the magnitude of the extrusion rate (m) of the printing parameters, where

$$\omega_1 = W_2/(W_1 + W_2 + W_3) \tag{4-2}$$

$$\omega_2 = W_4/W \tag{4-3}$$

Based on the silicon-hydrogen ratio and ethylene content, the mass of MH180 is:

$$W_3 = A \times (W_1 \times C_1 + W_2 \times C_2 + W_5 \times C_4)/(C_3 \times 27) \tag{4-4}$$

The sum of the ethylene content in MP50C_1、$C_2C_4$00, DT2750 and MP450 is respectively. is the hydrogen content of MH180; is the mass of MP450 consumed, approximately equal to the mass of the catalyst ink, calculated as. The mass relationship formula and associated preset values between these materials are entered into an Excel spreadsheet, and finally the mass of the DT2750 is manually adjusted to the preset value, and then the mass of all components can be determined. $C_3W_5W_5 = W/m\omega_1$

After calculating the mass of the material, the MP5000, DT2750 and MH-180 were stirred in a stirrer at 1000 rpm for 3 min, then A380 was added and stirred at 1500 rpm for at least 10 min until the substrate was well mixed. Finally, the material is transferred to a print container, where it is ready for printing after 30 minutes of degassing in a vacuum foam defoamer.

4.3 Summary of this chapter

This chapter introduces the preparation of soft materials for embedded multi-material 3D printing. Firstly, the molding mechanism of addition molding room temperature vulcanized silica gel was introduced, and the printing process was described.Additive molded room temperature vulcanized silicone rubber is a silicone rubber material that can be cured at room temperature, with excellent chemical stability, high temperature resistance, waterproof and moisture resistance, aging resistance, chemical corrosion resistance and other properties[44]。Next, the 3 are listedThe experimental raw materials used in the D process are described in detail and the preparation method of each material is detailed: the catalyst ink used for silica gel printing contains a platinum catalyst and a low-viscosity vinyl silicone oil MP450.The conductive ink is made of platinum catalyst and MP450. The support matrix is made of MP5000, DT2750, MH180 and A380.

Operation and experimental results of an embedded multi-material 3D printing system

5.1 The operation process of an embedded multi-material 3D printing system

3D printing technology is mainly divided into several steps: first, use CAD software to carry out 3D design, and save the design file as . STL format. The STL file is then imported into the slicing software, which breaks down the STL file into multi-layered planes and generates the appropriate G-code to control the operation of the 3D printer. Next, upload the G-code into the 3D printer and load the required materials. Finally, the 3D printer prints out the physical model layer by layer based on the G-code and the selected material until the entire design is completed.

5.1.1 Printhead calibration

The 3D printing system is equipped with two nozzles, and in the installation process, the installation of the syringe, the installation of the syringe and the small length error of the needle tube will cause the deviation of the position of the two nozzles in the three directions of XYZ, and then cause the problem of fault and large error in the printing process. Therefore, the first thing to do before printing is to calibrate the printhead.

In the XY two directions, the calibration method is as follows: control the nozzle 1 at a specified position in the XY plane, such as (200mm, 200mm). Draw a dot on a piece of A4 paper in advance, place its water on a hot bed, and align the dot with the tip of the needle of nozzle 1 to fix the paper. Put back the sprinkler 1, manipulate the sprinkler 2 to the same position, observe the deviation between the needle and the point, and adjust the sprinkler in 0.1mm increments until the two are aligned. Write down the position of the sprinkler 2 at this time, and make a difference with the original coordinates, and obtain the offset. Set the offset in the T1 instruction in the configuration file and verify it twice.

In the Z direction, the calibration method is to glue a thin piece of tin flat to the hot bed and clamp one of the pens of the multimeter to the tin sheet. Control the nozzle 1 at a specified position in the XY plane, such as (200mm, 200mm). Clamp the other pen of the multimeter on the needle of the nozzle 1, and slowly move the Z-axis at 0.1mm until the multimeter shows resistance, indicating that the circuit is turned on, that is, the needle has touched the tin sheet, and the Z-axis coordinates are recorded at this time. Printhead 2 repeats the operation and records the Z-axis coordinates. The Z-axis deviation is obtained by the difference between the two Z-axis coordinates, which isset in the T 1 command in the configuration file and verified twice.

5.1.2 Slicing process

The slicing software used in this 3D printing system is simplify3D. It can cut the 3D model into multiple layers, generate instructions that the printer can understand, and control the printer for 3D printing. The slicing software features support for a wide range of 3D printers and materials, an intuitive and easy-to-use user interface, accurate model restoration, advanced support structures, real-time preview and analysis, and multi-material hybrid printing.

By transferring the design file to simplify3D and configuring the parameters of filling, support, speed, etc., the specific print path can be obtained and the G-code can be generated. Assign different parts of the design to different printheads to complete the slicing process of multi-material 3D printing, as shown in Figure 5-1.

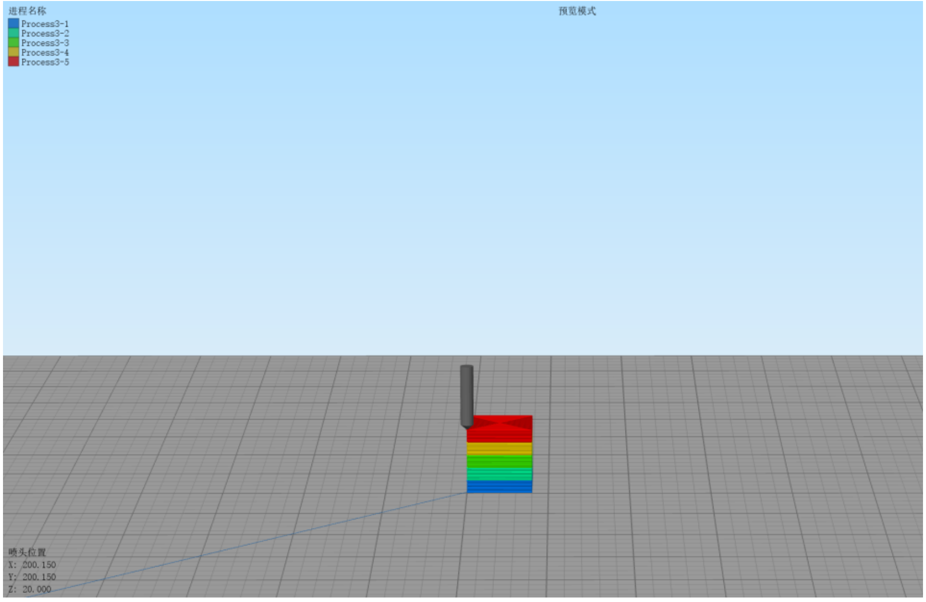


Figure 5-1 Slice preview in simplify3D

5.1.3 Printing process control and post-print processing

The 3D printing interface of this 3D printing system is Fluidd. Fluidd is an open-source 3D printing software that offers an intuitive user interface that can be used to control a wide range of 3D printers. Its user interface is designed to be specifically optimized for 3D printing, easy to use, and powerful. It offers a range of tools and setting options to help users easily control various aspects of the 3D printer, such as print speed, temperature, flow rate, and more. Users can adjust these settings with a simple drag-and-drop and point-and-click operation, and see the status and progress of the printer in real-time. Fluidd's user interface is divided into panels, each of which displays specific information and controls, such as the file browser, 3D model preview, print settings, print progress, and more. Users can open or close these panels as needed, and adjust their size and position to suit their workflow.

Figure 5-2 shows the basic interface of Fluidd, which can help users debug the 3D printer, such as XYZ axis movement, printhead discharge, and zero adjustment. Users can adjust parameters such as movement speed, pressure compensation, etc., according to the printing needs. In addition, the user can detect the temperature of the nozzle and the hot bed in real time.

Once the printing process is started, the user can monitor the printing process in real time through the Fluidd interface. As shown in Figure 5-3, users can monitor the remaining printing time, used consumables, extrusion flow, number of printing layers, printhead position, etc. In addition, users can also observe the trajectory of the printhead during printing and monitor the printing process, as shown in Figure 5-4.

After printing, put the container containing the supporting substrate into an electric blast drying oven and heat it at a constant temperature of 60 degrees Celsius for 120 minutes, as shown in Figure 5-5. Once the heating is complete, the finished print is removed from the container.

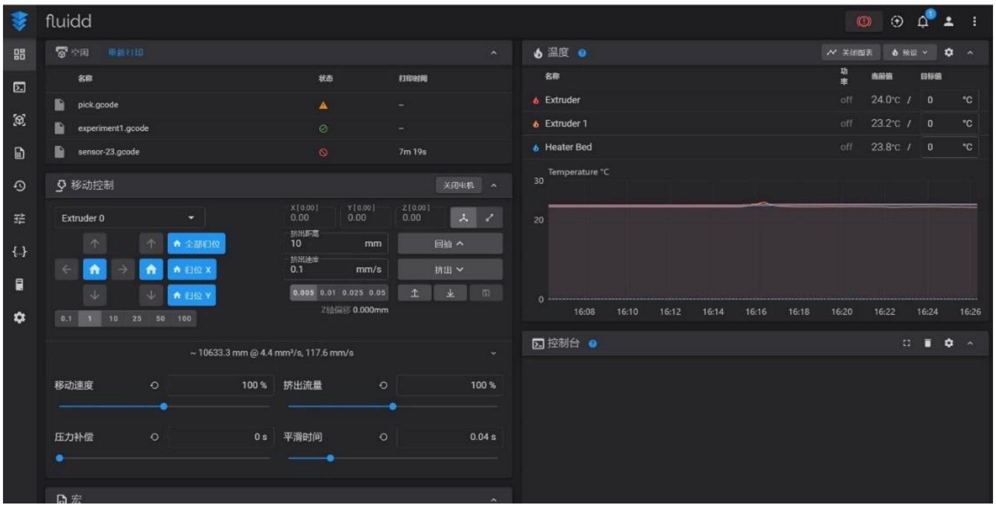


Figure 5-2 Basic interface of Fluidd

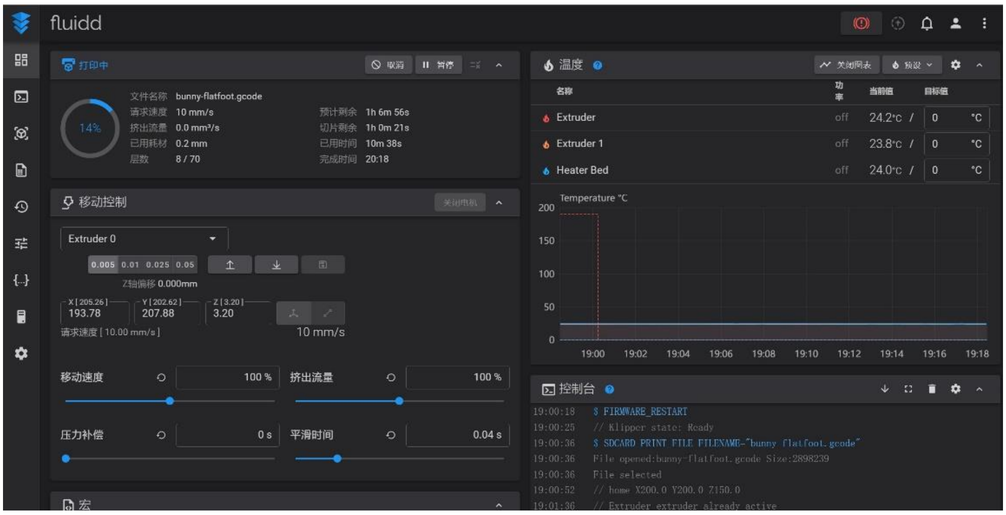


Figure 5-3 Fluidd printing interface

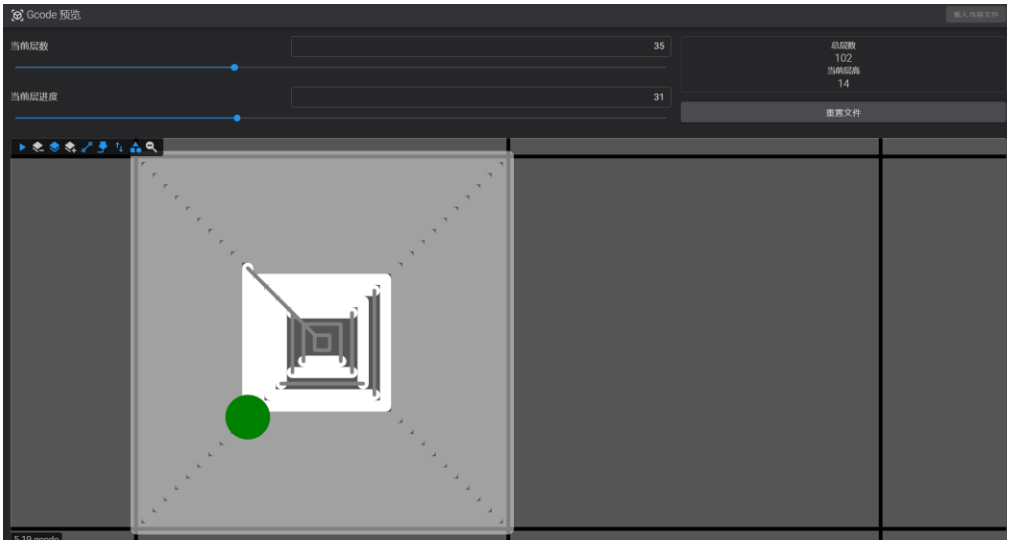


Figure 5-4 Trajectory monitoring during Fluidd printing

Figure 5-5 Electric blast drying oven

5.2 Experimental results

In this project, some simple structures were printed by using a built-up embedded multi-material 3D printer to verify the stability and accuracy of the 3D printing system. The focus is on the connection between the two materials, the dimensional error of the printed product, and the surface finish.

First, the 3D printer used transparent catalyst ink and blue catalyst ink to print a cube with a side length of 20cm. The blue part of the cube is longitudinally separated from the transparent part, and each part is 4 mm thick. The printing process needs to go through 4 printhead change processes, which can fully verify the printing effect at the junction of different materials, that is, the error of the height of the two printheads in the Z-axis direction. The printing process is shown in Figure 5-6. In the actual printing process, the printhead was changed accurately, and there were no problems such as misalignment and collision. As shown in Figure 5-7, the printing results show that there is no fault problem at the connection of different materials, the size error of the object is about 0.1mm, and the surface is smooth.

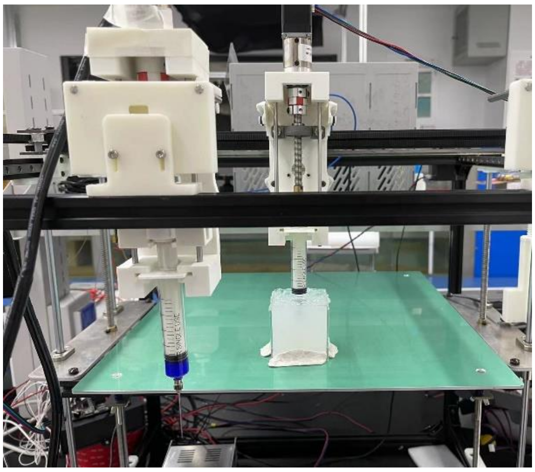


Figure 5-6 Experiment 1 printing process

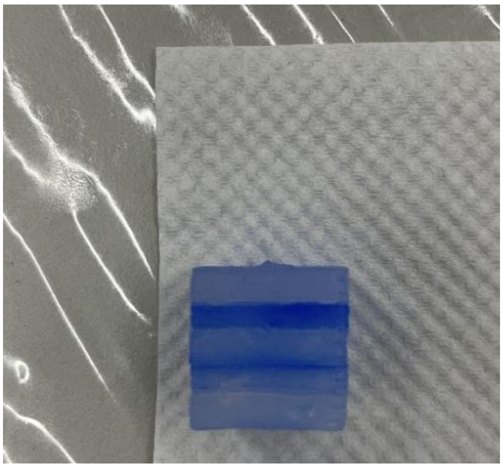


Figure 5-7 Experiment 1 finished product

In the second experiment, a transversely colored cube was also printed with transparent catalyst ink and blue catalyst ink. The cube is composed of four cubes with a side length of 10.3 mm, and the adjacent cubes are of different colors, as shown in Figure 5-8. The printing process goes through 3 printhead changes. The results show that there is no fault at the connection of different materials of the printed product, the size error of the object is about 0.1mm, and the surface is smooth.

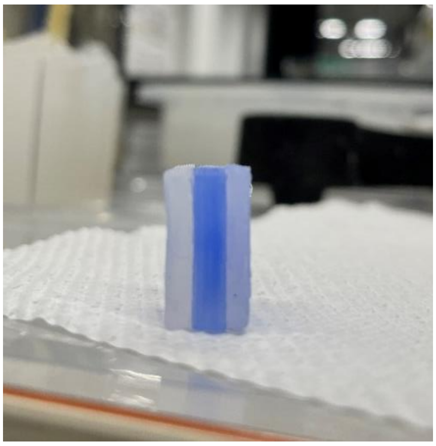


Figure 5-8 Experiment 2 finished product

In the third experiment, a tensile sensor was printed using transparent catalyst ink and conductive ink. The sensor is 90 mm long, 9 mm wide, and 1.6 mm high. The printing process needs to go through one printhead change process, and the schematic diagram of the printing process is shown in Figure 5-9. As shown in Figure 5-10, the conductive ink is well placed in the soft shell, the object size error is about 0.1mm, and the surface is smooth. This experiment demonstrates the potential of the 3D printing system in the field of soft robotics.

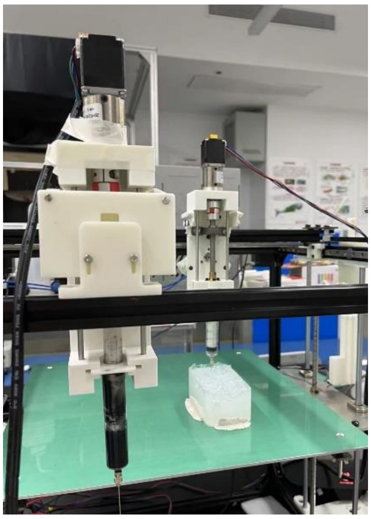


Figure 5-9 Experiment 3 printing process

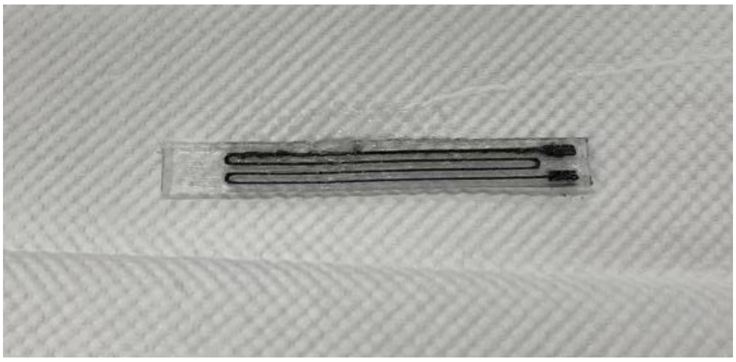


Figure 5-10 Experiment 3 finished product

5.3 Summary of this chapter

This chapter introduces the operation and experimental results of the embedded multi-material 3D printing system. Firstly, the operation process of the 3D printing system is introduced, including printhead calibration, slicing, process monitoring and post-print processing. By setting the deviation of the double printhead in the XYZ direction, the problem of fault and large error in the printing process is avoided. The slicing software uses simplify3D to configure parameters such as filling, support, and speed, obtain a specific printing path, and generate a G-code. The 3D printing interface Fluidd is used to complete the debugging of the 3D printer and monitor the printing process in real time. After printing, the container containing the supporting substrate is placed in an electric blast drying oven and heated at a constant temperature of 60 degrees Celsius for 120 minutes. Next, some experimental results are introduced, the experimental results show that there is no fault problem at the connection of different materials, the object size error is 0.1mm, and the surface is smooth, which verifies the stability and accuracy of the 3D printing system.

Conclusion

1. Summary of dissertation work

This project mainly focuses on the design and application of embedded multi-material 3D printing systems. Multi-material 3D printing technology has many advantages over single-material printing. Multi-material 3D printing technology enables the use of different materials in the same construction process, allowing for the creation of objects with more complex structures and morphologies. The work content of this project is mainly divided into mechanical structure design, control system design, soft material preparation and experiment.

In terms of mechanical structure, the design of the 3D printing system mainly includes the selection of the frame structure, the nozzle replacement device, the design of the nozzle and the design of the nozzle docking station. The printer was selected to be the CoreXY framework,It makes the print head stable during movement, reduces the vibration and inertia of the movement, and thus improves the printing speed and accuracy. The nozzle changer uses a nozzle changer to switch materials. The device uses the principle of series elastic actuators to convert the fixed torque and complete the locking and unlocking of the nozzle[33]。 The nozzle adopts an integrated design, which uses the spindle to rotate to realize the push of the syringe, and uses the keyhole to dock with the nozzle changing device. Height-adjustable sprinkler stops are used to park unused sprinklers and can be fine-tuned during assembly.

In terms of control systems, The 3D printing system uses firmware Klipper, based on its higher printing speed and accuracy, Easier configuration and commissioning[42]。In this control system, the upper computer adopts a Raspberry Pi with efficient computing power, and the lower computer uses the 3D printer motherboard BIGTREETECH Octopus Pro, which better supports Klipper's high-speed motion control algorithm and improves the printing speed and quality. The main profiles in Klipper are the main profile, the tool-lock profile, and the pick-and-place profile[43]。 The main profile configures the stepper motor Information such as the control pins, limit switch position, maximum range of movement, and the speed at which the motor is returned to the origin, for the X, Y, and Z axes.The tool lock profile defines a manual stepper motorto control the printer's tool lock.The Pick & Place profile primarily defines the process of pick-up and return of the sprinkler.

In terms of material preparation, the supporting matrix in the 3D printing process is additive RTV silicone rubber, which is usually composed of vinyl silicone oil, hydrogen-containing silicone oil, platinum catalyst at the sealing end (or side group), and corresponding fillers, additives, inhibitors, etc. can be added as needed to meet the requirements of mechanical, optical or electrical properties. The catalyst ink contains platinum catalyst and low viscosity vinyl silicone oil MP450 with a mass ratio of 1:125. The conductive ink is made of platinum catalyst and MP450 as raw materials, and the mass ratio is 1:250.

After setting up the printing system, the project conducted some experiments to verify the usability of the printing system. The slicing software used in the printing system is simplify3D, through which the printing path of different materials is designed and the G-code is generated. After the printing starts, the 3D printing interface Fluidd is used to monitor the printing process in real time. In this project, a 3D printer was used to print a cube with alternating colors in the longitudinal and transverse directions and a simple tensile force sensor, and the experimental results verified the consistency of different printheads in the X-axis, Y-axis and Z-axis, as well as the stability, accuracy and application potential of the printing system.

2. Job outlook

Two different materials were used for this project, so two printheads were used. In the future, we will increase the number of printheads to achieve more kinds of printing materials, and complete products with more complex structures and more diverse functions. The current multi-material 3D printing system mainly realizes the switching of materials by automatically changing the printhead, but with the increase of the number of printheads, more materials can be printed at the same time, which further improves the flexibility and efficiency of printing. To achieve this, the printing system needs to continue to optimize the performance of the embedded multi-material 3D printing system, including speed, accuracy, and material efficiency. In addition, the application of embedded multi-material 3D printing systems in specific fields can be further studied. For example, in the medical field, the printing of biodegradable materials can be researched and developed for customized medical devices and tissue engineering; In the aerospace field, we can study the application of high-temperature wear-resistant materials for printing to meet the needs of special environments; In the field of electronics, it is possible to study the application of conductive materials for printing, which are used for flexible electronic devices. Finally, the control method and software interface of the embedded multi-material 3D printing system can be further improved to improve the operation convenience and user experience of the system. By improving the slicing software and developing a more user-friendly interface, the system is easier to operate and debug, and provides more functions and options.

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