Development of a Digital Multi-material Sand Monolithic Printing and Forming Device

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Abstract

Based on the working principle of micro-drop jet sand 3D printing technology, this paper designs and processes the relevant equipment and its control system according to the design ideas, optimizes the relevant machinery and control system, and develops a multi-material sand type integral printing and forming equipment. The overall structure of the equipment is a sand box forming platform in the working area, a bi-directional sand laying printing structure and a vacuum sand loading structure and other mechanical devices. The PLC-controlled host computer software automatically identifies the slice information and carries out sand additive manufacturing to realize bi-directional sand laying multi-material sand printing, which effectively improves the efficiency of sand 3D printing.

Keywords

Multi-material, sand 3D printing, mechanical device.

1. Introduction

The application of sand mold 3D printing technology is wide and it integrates CAD computer three-dimensional design, 3D printing technology [1-2], digital automation control technology, and sand mold casting technology. It uses a layered printing method with binding agents and refractory materials to directly manufacture complex and high-precision sand molds (cores). It has high flexibility, speed, and accuracy, providing convenient conditions for new product development, reducing the cost of development and production, and increasing the added value of products [3]. It is particularly suitable for the development and production of single-piece, small-batch, personalized, and complex-shaped castings.With the development of high-end manufacturing industries, single-material sand molds can no longer meet the increasingly demanding requirements for high-performance and complex castings. In response to the complex geometric features, significant differences in wall thickness, and high requirements for dimensional accuracy and quality performance of high-end castings in fields such as aerospace and power machinery, the digital multi-material sand mold integrated printing technology is proposed. This technology relies on the integration and innovation of multi-material matching, multi-process coupling, and major system equipment to achieve precise control over the overall printing and forming of multi-material sand molds (cores) and the performance of high-end castings [4-5].

This article provides an overview of the mechanical devices and control systems of digital multi-material sand mold integrated printing equipment, summarizes their design principles and working principles, and innovatively achieves bi-directional sand deposition printing of multi-material molds, which can be widely used in the field of high-performance casting manufacturing.

2. Primary Parameters of Test Apparatus

According to the research and development product quality specifications and technical requirements, a technical agreement is formulated to specify the main technical parameters of the digital multi-material sand mold integrated printing equipment, as shown in Table 1.

Table 1. Primary parameters of test apparatus

Device Parameters:	Range/Size	Unit
Forming size	1000×800×600	mm
Printing efficiency	≥90	$L \cdot h^{-1}$
Printing layer thickness	0.3-0.6	mm
Printing speed	≥200	$Mm \cdot s^{-1}$
Error range	≤±0.3	mm

3. Design Idea

Based on the technical parameters and process route of the multi-material sand mold integrated printing equipment, the design concept of the forming equipment is developed, as shown in Figure 1.

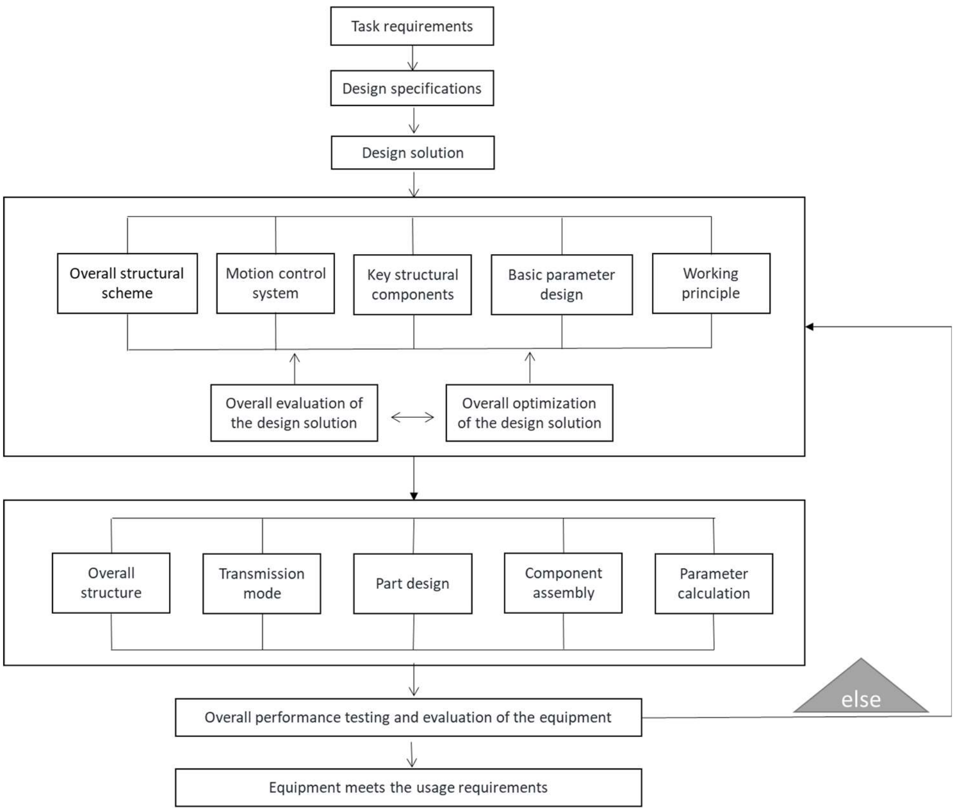


Figure 1. Design concept of multi-material integrated 3D printing equipment

During the design work of the multi-material sand mold integrated printing equipment, the design scheme is formulated based on the design parameters and functional requirements, and the most suitable structure is selected through analysis and validation. However, during the design process, continuous optimization and improvement will be carried out through scientific analysis and validation to ensure that the designed equipment has scientific and rational performance.

4. Mechanical Structure and Working Principle of the Equipment

The workflow of the multi-material sand mold whole-printing molding equipment is shown in Figure 2. The equipment mainly stores the raw materials in the upper sand box through a vacuum material device. As the input slicing program starts the sand mold printing work, firstly, the upper sand box puts the raw materials into the sand laying device. The sand laying device runs synchronously with the printing device. By program control, the raw materials are laid into the required layer thickness on the sand box forming platform. According to the slice pattern, the printing box prints the corresponding pattern on the forming platform. Through continuous repetition of the process, the sand mold product with complex features, high dimensional accuracy and good quality performance is gradually layered and formed.

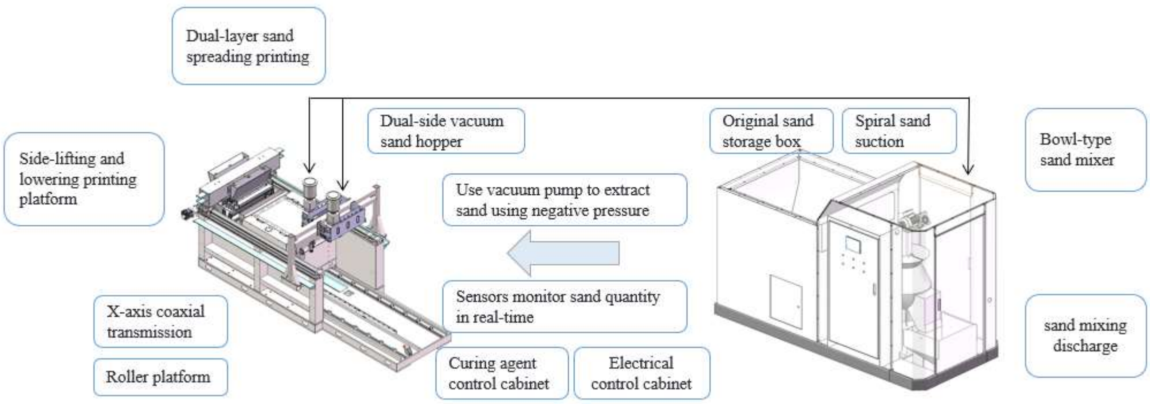


Figure 2. Workflow of multi-material integrated printing and forming equipmen

Printing equipment's mechanical structure mainly includes the main mechanical device, sand molding platform, two side frames, sand laying and printing device, and upper sand device. Below we will provide a detailed introduction and describe the working principles of the main mechanical devices.

4.1. Main Mechanical Structure

Figure 3 shows the main mechanical structure of a multi-material integral printing device. A pair of transmission modules are installed on both sides of the structure, and an additional pair of guide rails are added as auxiliary rails to enable the transmission modules to bear sufficient load. At the same time, a transmission shaft is designed to control the synchronous movement of the two modules through a single motor and reducer. This design accommodates both coaxial operation of the dual modules and ensures the precision of linear motion [6].

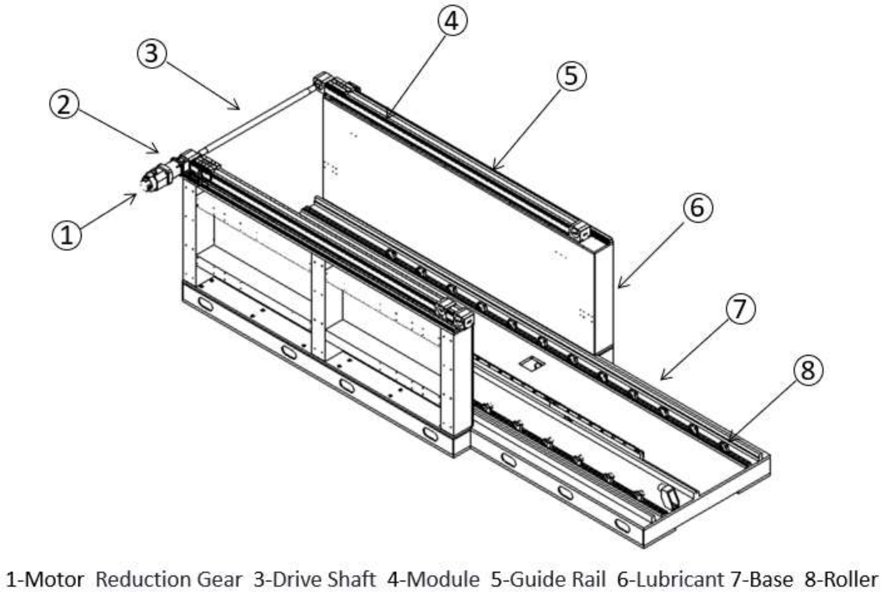


Figure 3. Main mechanical structure

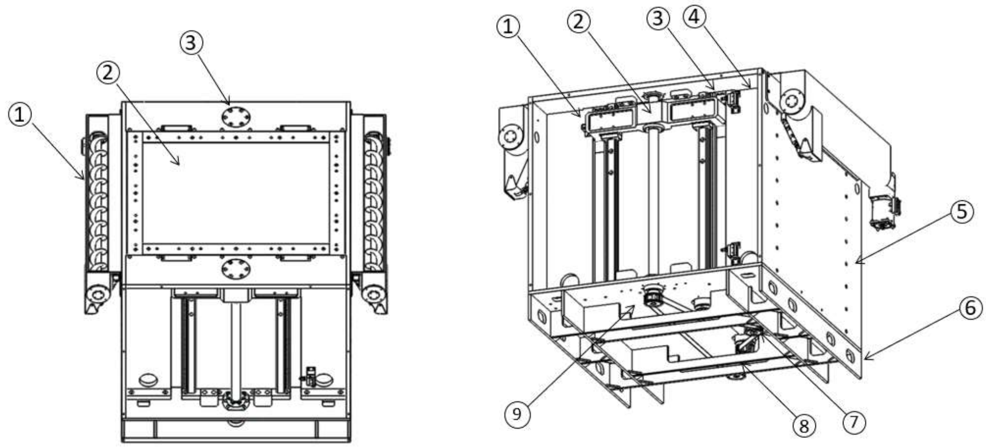
Design a dedicated base and support for sand molding platform and sand laying printing mechanism respectively, using welding with ordinary steel. To reduce the parallel motion trajectory error between the sand molding platform and the sand laying printing mechanism, the support is fixed above the base through integrated processing to ensure parallel accuracy and facilitate installation and debugging.

4.2. The Sand Molding Platform

The sand molding platform is one of the important mechanisms that determine the reliability and stability of multi-material integral 3D printing equipment. During the equipment operation process, each layer is printed by lowering the forming platform according to the layer thickness, and then sand molds are adhered and formed in the Z-direction. In the design process, the following issues have been addressed:

(1) To avoid the formation of a sand molding platform that is too high, causing difficulties in sand removal, a lifting structure on the side of the platform has been designed to lower the height of the sand molding platform. Compared with the lifting structure located in the central part of the lead screw, the lead screw's lateral lift structure saves more than 1/3 of the space travel.

(2) Considering that after leveling the printing platform, two sets of lead screws raise the platform from the side simultaneously, it is necessary to synchronize control the lifting of the printing platform using both sides of lead screws. To address the issue of synchronous operation of the two sets of lead screws, a servo motor and reducer are used to drive an active wheel, and two tensioning wheels are adjusted to adjust the tension of the synchronous belt, which drives the driven wheels at both ends of the lead screw axis to achieve synchronous operation.



1-Spiral Sand Separator
2-Printing Platform
3-Transmission Lead Screw

1-Home Sensor 2- Lifting Beam 3-Limit Switch
4-Sand Box Side Plate 5-Sand Box Front Plate 6-Sand Box Base/Stand
7-Drive Wheel 8-Tensioning Wheel 9-Driven Wheel

Figure 4. The mechanical device for the sand molding platform

The mechanical device for the sand molding platform is a combination of sand storage and Z-direction layer-by-layer printing functions, with added spiral centralized waste sand cleaning equipment. Figures 4(a) and (b) show the main structure of the mechanical device for the sand molding platform.
To calculate the required moment of inertia J for the screw movement based on the maximum load of the forming platform.
The formula for screw moment of inertia is as follows: $J_{B}= \frac{\pi\rho L_B D_B^4}{32}$;
Based on the known parameters: π (pi) = 3.1416, lead screw density ρ = 7900 kg/m3, effective length of the lead screw LB = 0.885 m, and lead screw diameter DB = 0.04 m.

$$J_{B}= \frac{\pi\rho L_B D_B^4}{32}=\frac{3.1416\times7900\times0.885\times0.04}{32}=1.76\times 10^{-3}\text{kgm}^2;$$

The inertia required for the platform lifting motion due to the load supported by the lead screw is J:

$$J_{L}=m\left(\frac{P_B}{2\pi}\right)^2;$$

The known parameters are: screw pitch PB = 0.01m, maximum load mass m = 1500kg.

$$J_{L}=2\times\frac{1}{2}m\left(\frac{P_B}{2\pi}\right)^2=2\times\frac{1}{2}\times 1500\times\left(\frac{0.01}{2\times3.1416}\right)^2=3.80\times 10^{-3}\text{kgm}^2;$$

The total load inertia $J=2\times J_{B}+J_{L}=2\times1.76\times 10^{-3}+3.8\times 10^{-3}=7.32X10^{-3}\text{kgm}^2$;
To calculate the required torque T_M for the lead screw motion based on the maximum load of the forming platform, first we need to determine the starting torque T_S according to the formula.

$$T_S=\frac{2\pi\quad m(J_m+J)}{60t_i}$$

Based on the given parameters:Pi (π) = 3.1416, motor speed in RPM (Nm) = 100 RPM, motor inertia (Jm) = 1.53X10^-3 kgm^2, total load inertia (J) = 7.32X10^-3 kgm^2, and acceleration time (ti) = 0.75s.

the starting torque Ts==$\frac{2\pi N_m(J_m+J)}{60t_i}$=$\frac{2\times3.1416\times100\times(1.53X10^{-3}+7.32X10^{-3})}{60\times0.75}$=0.123Nm

Next, calculate the load torque T_L required for the forming platform: T_L=$\frac{FP_B}{2\pi\eta}$;

Given the known parameters F=mg=14699.9946N, lead screw pitch P_B=0.01m, mechanical efficiency η=0.9,

the torque on the load T_L=$\frac{FP_B}{2\pi\eta}$=$\frac{14699.9946\times0.01}{2\times3.1416\times0.9}$=25.995Nm;

Since a safety factor S=2 is selected, the required torqueT_m must be 52.23Nm:

T_m=(T_L+T_S)×S=(0.123+25.995) × 2=52.23Nm

Based on the calculation, you can preliminarily determine the motor model and input the rotor inertia to confirm the motor torque TM = 7.16 Nm. When the required torque is greater than 5 times the motor torque, it is necessary to consider using a reduction device to improve torque matching. i_1≥$\frac{52.23}{7.16}$,so i_1≥8,

Considering an appropriate safety factor, complete the selection of the driving wheel, driven wheel, and synchronous belt according to the calculation method specified in JB/T 7512.2-2014 Arc Tooth Synchronous Wheel Selection.

4.3. Bidirectional Sand Paving and Printing Integrated Device

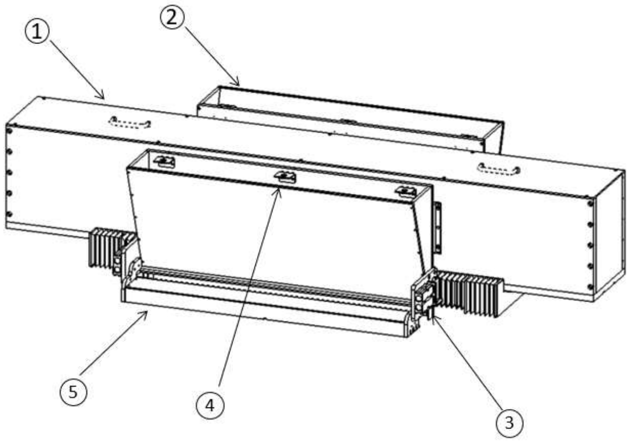
The integrated sand laying and printing device for bidirectional sand deposition adopts a layout with multiple printheads to effectively improve the printing efficiency of sand molds. By integrating the sand laying and printing mechanisms, it enables the adjustment of the sand laying and printing process sequence, as well as the positioning of the sand laying work, through the upper computer operation. This allows for the realization of multi-material layered printing, resulting in sand molds made of multiple materials.

The layout of the printing printheads is crucial for improving the efficiency of the multi-material integrated printing molding equipment. There are generally two layout options:

(1)The first option is single-head printing, which utilizes a single printhead to print the current slice pattern on the sand deposition plane along the X and Y coordinates. This layout can achieve the printing of sliced shapes based on the width of the printhead and is suitable for printing complex sand molds with small dimensions. However, if printing large-scale sand molds, this approach may result in lower efficiency and potential defects such as adhesive layering or weak bond strength

(2)The second option is to use a combination of multiple nozzles for printing. Compared to single-nozzle printing, multi-nozzle printing reduces the printing steps in the Y-axis direction, and under the same project speed, the printing efficiency of each layer of the sand mold is increased by at least 65%.

Therefore, the multi-material integrated printing and forming equipment adopts the method of combination-type multi-nozzle printing, which improves the printing efficiency significantly by arranging the nozzle structure and streamlining the printing process.



1-Print Box 2-Sanding Box 3-Infrared Heating
4-: Material Level Sensor 5-Pneumatic Cylinder

Figure 5. Bidirectional sand paving and printing integrated device

The mechanical structure of the integrated bidirectional sand laying and printing device shown in Figure 5 relies on the printhead box as the crossbeam, with sand deposition boxes integrated on both sides. The crossbeam is driven by the drive mechanism of the vertical module to reach the working position. It performs the steps of sand laying, leveling, printing, and heating by opening the sand deposition box through a cylinder. The complex and high-precision sand mold products gradually solidify and form with high strength.

By applying the comprehensive application of the principles, methods, and devices mentioned above, it is also possible to effectively solve the severe problem of print layering caused by the thickness of the sand deposition layer and the adhesive content. Considering the strength of the crossbeam and the reduction of inertia and torque generated by variable-speed and variable-direction motion on the module and auxiliary rail, the printing crossbeam and sand deposition box are made of 6061 aluminum alloy material. On one hand, 6061 aluminum alloy not only has certain strength and mechanical properties but also has a lighter weight. On the other hand, 6061 aluminum alloy itself has good wear resistance and corrosion resistance.

4.4. The Material Replenishment Device

The material replenishment device is a structure for storing sand mold printing materials in the sand box. Its main purpose is to quickly replenish the materials after they are used up, enabling continuous operation of the equipment.

In the traditional sand box, additional materials need to be added after the materials are depleted in order to continue the sand mold printing function. Through the design, improvement, and enhancement of the material feeding function, the problem of low printing efficiency caused by material replenishment has been effectively solved. With the assistance of a level sensor, the signal is integrated into the upper computer software program, achieving efficient continuous printing of multi-material sand molds in the integrated printing and forming device.

The material replenishment device (refer to Figure 6) mainly consists of a vacuum suction hopper and a sand feeding box. The vacuum suction hopper automatically sucks the materials from the material area into the barrel through vacuum negative pressure. The barrel has a valve for automatic control of material discharge, which is used for replenishing the material when it runs out in the sand box.

The sand feeding box is the main storage device for the sand box's materials. When the sand box detects insufficient materials, the sand feeding box quickly replenishes the sand box with materials. Inside the sand feeding box, there is a spiral controlled by a stepper motor, which can be observed through an observation window.

The spiral device evenly and smoothly distributes the materials released from the vacuum hopper in the sand feeding box. This ensures that the sand box is always uniformly filled with materials when receiving them, avoiding errors in signal transmission caused by the level sensor. The vacuum hopper and the sand feeding box have primary and secondary material storage functions. By coordinating the use of both, the problem of insufficient time for material replenishment during the printing process is effectively solved, realizing efficient and continuous sand mold printing of the equipment.

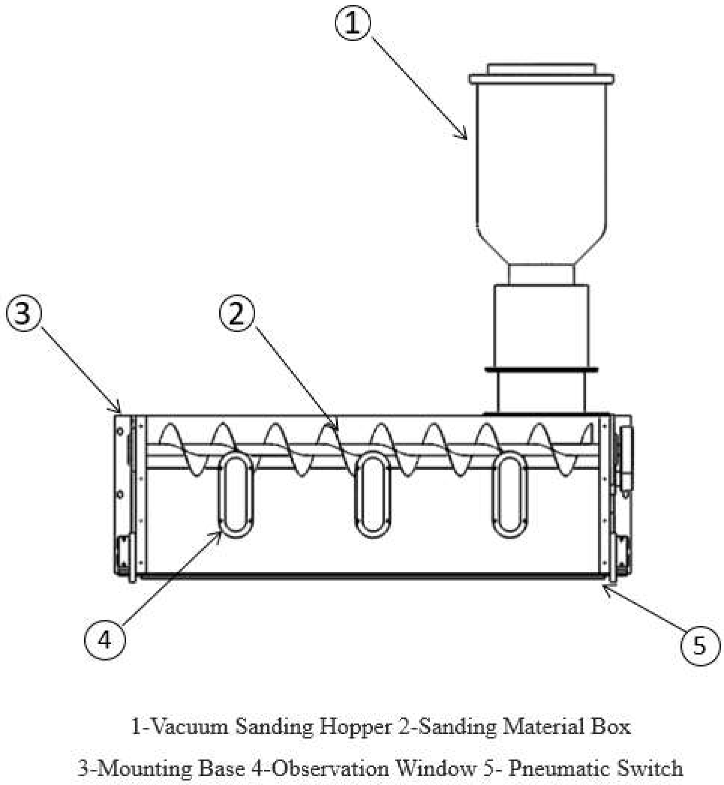


Figure 6. The material replenishment device

5. Design of the Control System

The control system is the soul of realizing the automation of equipment production. The multi-material sand mold integrated printing and forming device is an automated sand mold 3D printing device equipped with a program control system [7]. Its control system can import the 3D model of the part into slicing software through digital program processing, convert it into surface patterns, and then import them into the upper computer software for pattern recognition. The processing information of each layer is extracted and transmitted to the control system, which controls the multi-material sand mold integrated printing and forming device through software and hardware communication to start the automation process of sand mold printing according to the requirements of the model [8]. Figure 7 shows the design concept for motion control.

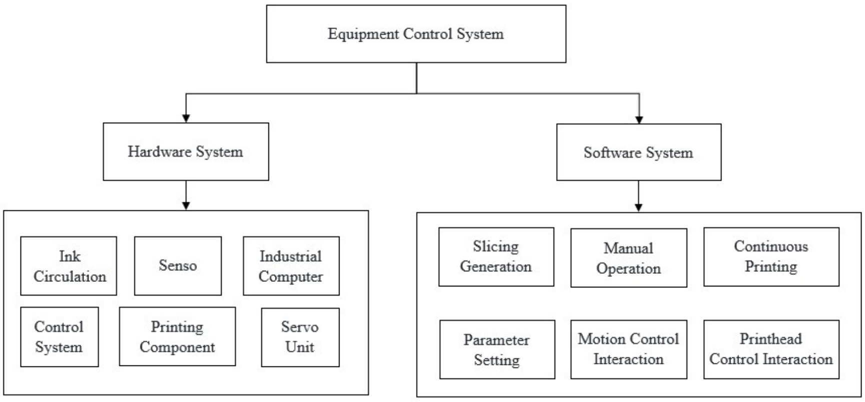


Figure 7. Motion Control Design Ideas for Multi-Material Additive Manufacturing Equipment

In fact, the main control object of the multi-material sand mold integrated printing and forming device is the movement of the axes, and the complex sand mold printing of the device is achieved by controlling the axes. The main way of movement is to pre-identify the slice pattern of the current layer and transmit signals during printing. By controlling the movement of each axis to the corresponding position, the print head control board is given a signal to start inkjetting, thereby quickly bonding the raw materials laid on the forming platform into a sand mold with certain strength according to the imported model's sliced pattern.

The control system of the device controls the motors or axes to perform their work. The internal logic uses PLC motion control programs as a communication bridge, relying on the PLC controller to interact with the print head controller and ink system to enable multi-channel printing and complete additive manufacturing of multi-material sand molds. The upper computer software adjusts parameters such as printing speed, grayscale level, and sand deposition layer thickness to achieve the goal of automatically printing high-precision sand molds.

6. Conclusion

This article primarily focuses on the research and design of new equipment and processes for sand mold 3D printing. By studying key technologies for digital multi-material sand mold integrated printing, a method for designing and manufacturing digital multi-material sand molds with integrated forming is established. An independently developed digital multi-material sand mold integrated printing and forming equipment, with a molding range of 1000×800×600mm, has been researched, developed, and debugged. The equipment has a compact and aesthetically pleasing overall structure, and the forming accuracy meets the required standards.

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