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Design of a Parallel Decoupled Manipulator for 3D Printers

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Abstract: *This study designed and implemented a novel parallel decoupled manipulator with the aim of enhancing the quality and efficiency of 3D printing. By optimizing the structure of the manipulator, the surface quality problem caused by the support structure in traditional 3D printing was solved, and the printing precision and stability were improved. This manipulator module is suitable for the v25 printer, adopts a delta design, has three degrees of freedom, and meets technical indicators such as the maximum printing size, positioning accuracy, printing speed, and working precision. The research contents include mechanism selection, 3D modeling, kinematic analysis, and trajectory planning. During the process of mechanism selection, the characteristics and applicability of various parallel mechanisms were comprehensively considered, and finally the most suitable structural form for 3D printing needs was determined. Through accurate 3D modeling, the visual design of the manipulator was realized, providing a basis for subsequent analysis and optimization. In terms of kinematic analysis, the motion characteristics and laws of the manipulator were deeply studied to ensure the accuracy and reliability of its motion. In the aspect of trajectory planning, a reasonable motion path was formulated to improve the printing efficiency and quality.*

Keywords: *Parallel Manipulator; Decoupling Mechanism; 3D Printing; Kinematic Analysis*

1. Introduction

Scientific progress drives the development process of industrial automation and promotes industrial automation to a new level, making fully automated production equipment become the mainstream and gradually replacing manual operation [1]. With the development of science and technology, robots are widely used. Among all kinds of robots, industrial robots are the most successful in practical applications, mainly used in automobile, electronics, mechanical processing and other fields [2]. Modern robots refer to industrial robots, also known as serial robots [3]. Compared with the series robot, the parallel robot has the advantages of large stiffness, stable and compact structure, strong bearing capacity, small accumulated error, high accuracy and good dynamic performance [4].

The earliest high-speed parallel manipulator was invented by a French doctor named R. Clavel in 1985. The parallel mechanism is called Delta parallel mechanism [5]. British scholar Gough designed a tire testing machine in 1947, which is very close to the 6-6 parallel robot now recognized, and is the earliest known six-legged parallel robot [6]. ABB UK developed IRB series parallel robots in 1999, and introduced computer vision into parallel robots [7]. An intelligent sorting robot developed by Japan's Yaskawa Electronics Co., Ltd. is widely used in automobile parts assembly and household appliance industry, and uses binocular vision to achieve accurate positioning and grasping of parts [8].

China needs to improve the automation and informatization level of industry and manufacturing industry. Robots are an important part of industry and manufacturing, and an important link to improve the level of industrial automation [9]. At present, China is the world's largest industrial robot market, with the largest installation volume in the world [10]. However, the proportion of domestic industrial robots is not high, and the global sales volume is lower than that of Japan, Germany, the United States and other developed countries [11]. Therefore, it is of great significance to develop China's independent industrial robot technology and design high-performance and low-cost industrial robots [12]. Compared with European and American countries, China's parallel robot research started late. Professor Huang Zhen of Yanshan University is one of the founders of China’s parallel robot research [13]. In the context of the reduction of the dividend of the domestic population, Delta parallel robot has been rapidly developed with its unique advantages, and is widely used in high-precision fields [14]. In the research of glass handling robot, series robot is the main. Liu Zhengyong summarized three common series configurations of glass substrate handling robots in the FPD industry at present: vertical multi-joint type, plane multi-joint type, and cylindrical coordinate type [15].

A new type of parallel glass handling manipulator studied in this paper can complete the grasping and handling of glass. The suction cup can quickly absorb the glass and can adjust itself to adapt the glass to different placement methods from multiple angles and transport it to the designated place. It greatly improves the handling efficiency and reduces the labor cost.

This study aims to design and implement a novel parallel decoupled manipulator for 3D printing technology. Through detailed analysis and performance testing, its performance and feasibility were verified, improving the robot's working accuracy and stability, reducing printing costs, and enhancing printing efficiency. The research content includes designing and implementing a more efficient and stable decoupled manipulator for 3D printers, Compare its performance differences with that of the serial robotic arm and discuss the influence of decoupling effect on printing quality. The new parallel decoupling robotic arm can solve the surface quality problem caused by the support structure, improve printing precision and stability, and has broad application prospects. The research results provide an important reference for 3D printing technology and robot control, and promote the mechanization and intelligent development of the manufacturing industry [16].

2. Overall Design Scheme

2.1. Design Objectives and Requirements

The design goal of this project is to develop a parallel decoupled manipulator module for 3D printers. This module can be adapted to the v25 printer, achieving fixed and controlled key parameters to improve the printer's performance and flexibility.

The maximum printing size of this manipulator module should be no less than 270mm in length, 205mm in width, and 205mm in height. The positioning accuracy should be X/Y: 11.25μm, Z: 1.25μm. Moreover, the maximum printing speed should not be less than 100mm/s, and the working precision should be between 0.05mm-0.2mm, to meet the requirements of efficient and rapid printing.

The module's control system should adopt a distributed architecture, as shown in Figure 2.2, to achieve good real-time performance and scalability. The control system should use open-source Arduino firmware and seamlessly integrate with the v25 printer's control system.

2.2. Technical Approach

In the mechanism selection, a parallel decoupled mechanism was chosen for 3D printing after comparing the spatial and freedom characteristics of serial, parallel, and decoupled mechanisms. In the modeling aspect, the mechanism's motion state was analyzed, and 3D modeling was performed using SolidWorks, with CAD used to export engineering drawings. In kinematic analysis, mathematical calculations were performed for forward and inverse solutions, interpolation methods determined the actual working space, and static and dynamic models were analyzed. For trajectory planning, the joint control principles were examined, and a simulation model was built using Mathematica. The performance comparison between Cartesian coordinate manipulators and parallel decoupled manipulators verified that the designed manipulator has stable motion and clear trajectory.

2.3. Main Technical Indicators

(1) Load capacity: 2.5kg;

(2) Motion range: length 270mm, width 205mm, height 205mm;

(3) Repeat positioning accuracy: X/Y: 11.25μm, Z: 1.25μm;

(4) Degrees of freedom: 3 degrees.

3. Mechanical System Design

3.1. Structural Design of the Parallel Decoupled Manipulator

The parallel decoupled manipulator studied in this paper is a three-degree-of-freedom parallel mechanism composed of a fixed platform, a moving platform, and three drive chains connected to the moving platform. Each drive chain includes a drive motor, lead screw-nut pair, decoupling chain, and link frame. The decoupling chain consists of two crossed rods that effectively reduce the coupling between the drive chains. The structural diagram of the manipulator is shown in Figure 1.

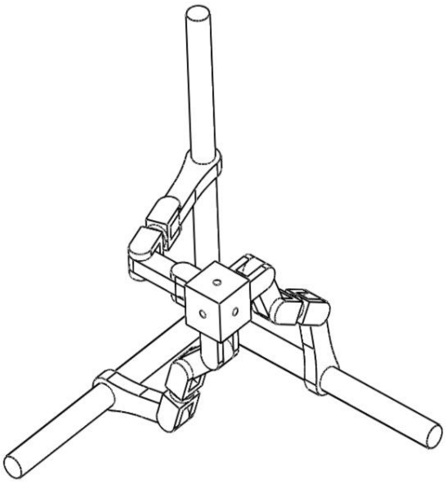

Figure 1: Structural diagram of a three-degree-of-freedom decoupled parallel manipulator.

3.2. Establishment of the Manipulator 3D Model

Each RUP chain consists of a rotational pair (R), a Hooke joint (U), and a prismatic pair (P). The rotational pair uses bearings to achieve rotational motion, and the Hooke joint comprises two perpendicular rotational pairs to allow two degrees of rotational freedom. The prismatic pair uses linear guides and sliders to enable linear motion.

The size parameters of the chains must be determined based on the overall manipulator size and motion range, as shown in Figure 3.2. The dimensions of the rotational pairs and Hooke joints should meet strength and rigidity requirements, leaving an appropriate safety margin. The stroke of the prismatic pairs should cover the manipulator's working space, and the length of the linear guide should be designed accordingly. The layout of the chains should be as compact as possible to minimize the manipulator's volume.

3.3. Motor Type Selection

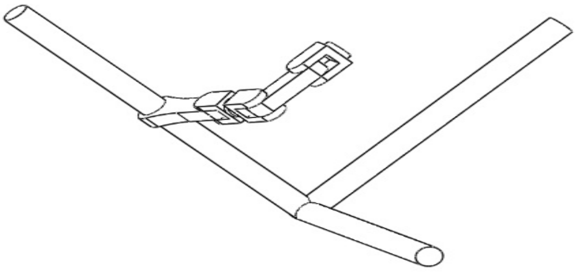

Figure 2: Branch chain of the manipulato

For the three degrees of freedom required by the parallel decoupled manipulator, three independent drive systems are needed. Considering a load capacity of 2.5kg and a maximum speed of 100mm/s with a peak acceleration of 20mm/s², high-performance servo motors were chosen as the actuators, as shown in Figure 2.

The lead screw-nut drive system is the transmission method adopted in this design, as shown in Figure 3. It offers the advantages of a high transmission ratio, high precision, and high efficiency. The diameter and lead of the lead screw should be selected based on the required transmission ratio and load capacity, while also considering the critical speed and stability of the lead screw. The nut can be either a ball nut or a slider nut; the former offers high precision but is more costly, while the latter is more affordable but prone to backlash.

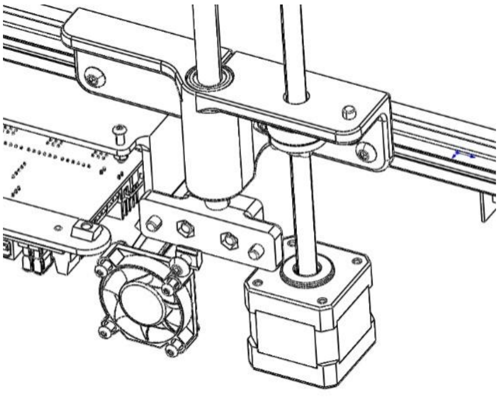

Figure 3: Screw and nut.

3.4. Structural Material Selection

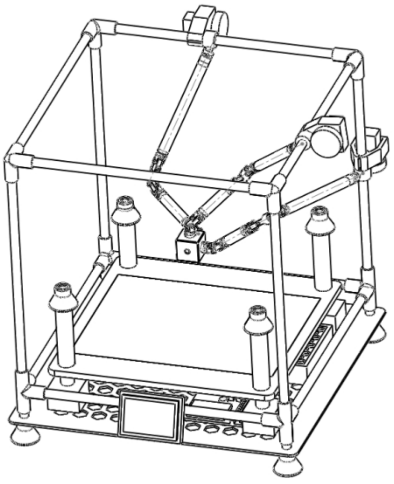

Figure 4: Assembly Diagram of the Manipu

Based on the 3D model design, as shown in Figure 4, the manipulator's joints and link components are manufactured using 3D printing technology. Common 3D printing materials such as ABS and PLA can be used. For critical components that need to withstand heavy loads, metal materials like aluminum alloy can be used, manufactured via CNC machining. The manipulator's base is made of metal materials such as steel and is installed with shock-absorbing pads to improve stability. All parts undergo surface treatment, such as anodizing or electroplating, after manufacturing to enhance their appearance and durability.

4. Kinematic and Dynamic Analysis of the Manipulator

4.1. Kinematic Analysis of the Parallel Manipulator

The forward kinematics is the process of determining the position and orientation of the moving platform given the lengths of the driving chains. For the three-degree-of-freedom translational parallel manipulator designed in this study, the forward kinematics is relatively simple and can directly establish the mapping relationship between the driving chain lengths and the moving platform position using geometric relationships.

Assume the length of the i-th driving chain is lil_ili, then the forward kinematic solution for the moving platform center PPP in the fixed coordinate system {B} is expressed as shown in Equation (1):

$$\begin{gathered} M_X=h_1+l_1\cos(180\text{-}\theta_1) \\ M_Y=h_2+l_2\cos\left(180\text{-}\theta_2\right) \\ M_Z=h_3+l_3\cos(180\text{-}\theta_3) \end{gathered} \tag{1}$$

Where M_X,M_Y and M_Z are the coordinates of the moving platform center M_X,M_Y,M_Z in the fixed coordinate system {B}.h1,h2 and h3are the initial heights of the i-th driving chain in the M_X,$M_Y$andM_Z directions, respectively. l1, l2, l3 represent the real-time lengths of the i-th driving chain. θ1,θ2,θ3 are the angles between the i-th driving chain and the horizontal plane.

Since the attitude of the moving platform remains unchanged, the posture matrix R of the moving platform relative to the fixed platform is an identity matrix.

4.2. Velocity Jacobian Matrix

The velocity Jacobian matrix describes the mapping relationship between the velocities of the driving chains and the velocity of the moving platform, serving as an important basis for evaluating the performance and speed control of parallel manipulators. Differentiating Equation (1), the velocity Jacobian matrix for this parallel manipulator can be obtained.

The elements of the velocity Jacobian matrix are composed of partial derivatives of positions with respect to angles. Define the joint variable velocities as $\dot{\theta}_1$,$\dot{\theta}_2$,$\dot{\theta}_3$. Their relationship with the end effector velocities is expressed in Equation (2):

$$\begin{bmatrix} \dot{M}_X \\ \dot{M}_Y \\ \dot{M}_Z \end{bmatrix}=\mathbf{J}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \tag{2}$$

Where each element **J** in the Jacobian matrix J_{ij} is the partial derivative of the end-effector velocity with respect to the joint variable. Differentiating the forward kinematics equations, we obtain Equation (3):

$$\begin{gathered} \frac{\partial M_X}{\partial \theta_1}=-l_1\sin(180\text{-}\theta_1)=l_1\sin(\theta_1) \\ \frac{\partial M_Y}{\partial \theta_2}=-l_2\sin\left(180\text{-}\theta_2\right)=l_2\sin(\theta_2) \\ \frac{\partial M_Z}{\partial \theta_3}=-l_3\sin(180\text{-}\theta_3)=l_3\sin(\theta_3) \end{gathered} \tag{3}$$

Therefore, the velocity Jacobian matrix J_{ij} is given as in Equation (4):

$$J=\begin{bmatrix} l_1\sin(\theta_1) & 0 & 0 \\ 0 & l_2\sin(\theta_2) & 0 \\ 0 & 0 & l_3\sin(\theta_3) \end{bmatrix} \tag{4}$$

The velocity Jacobian matrix for this parallel manipulator is a diagonal matrix, indicating that the velocities of the three driving chains correspond one-to-one with the velocity of the moving platform, showcasing its decoupling characteristics. Similarly, the angular velocity and angular acceleration of the end effector can be derived as shown in Equation (5):

$$\omega=\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{5}$$

Finally, the length changes of the driving rods for each joint can be calculated as shown in Equation (6):

$$\dot{\omega}=\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix} \tag{6}$$

The diagonal elements of the Jacobian matrix are only related to the tilt angles of the chains and remain constant throughout the entire workspace, facilitating precise velocity control. Based on the main technical indicators of this design and integrating the kinematic equations, the motion characteristics of the chains and end effector can be obtained within the range -150mm ≤ MXM_XMX ≤ 155mm, -120mm ≤ MYM_YMY ≤ 125mm, -100mm ≤ MZM_ZMZ ≤ 105mm.

As shown in Figure 5, the parallel mechanism consists of multiple chains, and the length of each chain affects the working space and load capacity of the mechanism, necessitating rational design. The figure illustrates the variation in chain length with changes in the driving angles concerning the design coordinates, as shown in Figure 6.

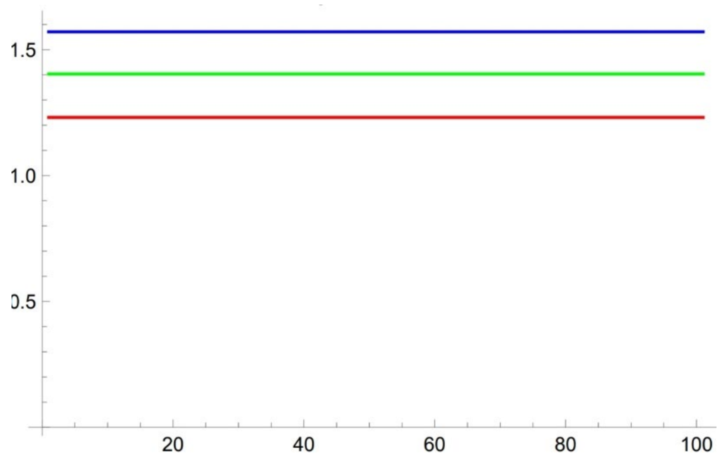

Figure 5: Joint angle

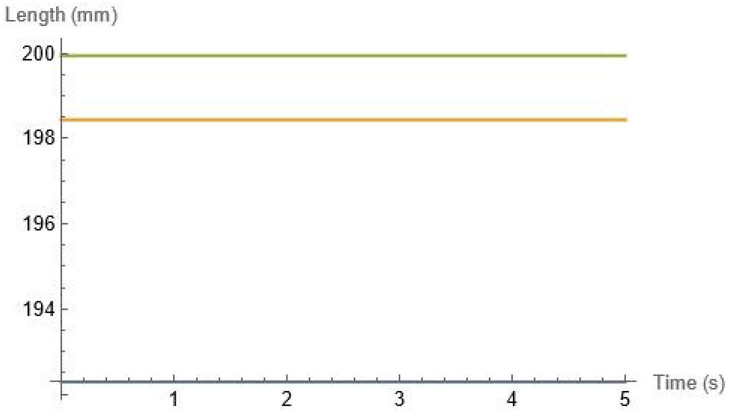

Figure 6: Length of branch chain.

5. Trajectory Planning of the Manipulator

Assume that the starting position of the manipulator is $P_0=(x_0,y_0,z_0)P_1=(x_1,y_1,z_1)$ and the target position is $P_1=(x_1,y_1,z_1)$

The position interpolation formula can be expressed as shown in Equation (7):

$$P(t)=P_0+t(P_1-P_0) \tag{7}$$

Where **t** varies between [0, 1]. A trapezoidal velocity curve is used to ensure that the speed and acceleration of the manipulator are within the given limits. The maximum speed v_{max} and the maximum acceleration a_{max} are specified values. The trajectory simulation for the manipulator during printing is shown in Figure 7.

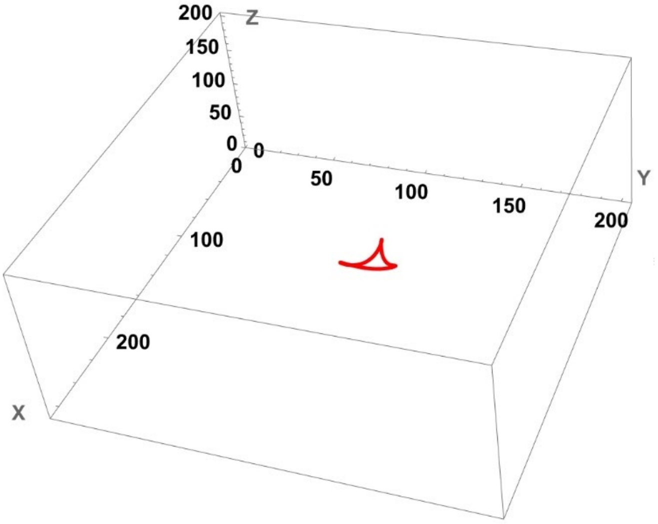

Figure 7: Manipulator Printing Trajector

6. Conclusion

This study successfully designed and implemented a parallel decoupled manipulator for 3D printing technology. Through detailed design and analysis, the manipulator demonstrated significant advantages in improving printing quality and efficiency. Specifically, the parallel decoupled manipulator module can be adapted to the v25 printer and met the expected technical specifications, including load capacity, motion range, repeat positioning accuracy, and degrees of freedom.

Experimental results showed that compared to traditional serial manipulators, the parallel decoupled manipulator exhibited greater stability and precision during printing, effectively reducing the impact of support structures on surface quality. Moreover, the module's control system adopts a distributed architecture, ensuring good real-time performance and scalability.

The outcomes of this research not only provide a new solution for 3D printing technology but also lay a solid foundation for future research and development in the field of robot control.

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