Structural Design of Large Heavy-load Stone Cutting Robot

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Abstract. Large quantities of stone cutting are generally done using robots. The current stone cutting robot drives the cutting machine to move and complete the cutting through the manipulator, but its moving range is limited. In response to this problem, a large heavy-duty stone cutting robot was designed in this subject. According to the design requirements and the functions to be realized by the equipment, the detailed structural design of each component of the stone cutting robot was carried out, and the static analysis of the robot arm and arm was carried out using ANSYS to ensure the safe operation of the equipment. The D-H parameter method was used to establish the kinematics model of the stone cutting robot, the positive kinematics equation was obtained by using the homogeneous transformation matrix, and the inverse solution of the kinematics equation was combined with the algebraic method. The proposed design was reasonable through experiments.

Keywords: Cutting robot; Structural design; Static analysis; Heavy load.

1. Introduction

In terms of stone cutting, hand push cutting machines, bridge cutting machines, and gantry cutting machines are currently on the market. The manual cutting machine has a low degree of automation and requires manual operation during cutting. Cutting irregular shapes has certain requirements for the operator's proficiency, and the heavier machine requires more manpower [1-2]. Improper operation can also threaten personal safety. The latter two cutting machines have a high degree of automation and relatively complete functions, but their equipment is large in size and takes up a lot of space, which has greater requirements for working space and higher prices [3-5]. Compared with the cutting machines on the market and robots that use manipulators to drive the processing head to complete the cutting, the cost is low, and it is a large-scale heavy-load stone cutting robot with very promising prospects. For example, the model SMART-CUT S/NC 800B is a fixed working table equipped with an electric transmission belt, which is convenient for loading and unloading of processed workpieces [6]. In the domestic research and development of stone processing machinery, some enterprises in Guangdong, Fujian, and Shandong have occupied the forefront position. For example, the CNC-5-800 five-axis stone cutting machine developed by Jinjiang Shengda Machinery Company can perform straight-line cutting, curved surface cutting, and drilling, and can complete five-axis linkage processing [7]. Hualong machinery company has developed a six-axis CNC bridge cutting machine, which belongs to the CNC625 series. It can process special-shaped stone plates, and can also process large-size stone plates and cut them into multiple small stone plates. YSD-QSQ infrared automatic bridge cutting machine series produced by Yongshengda Technology Co., Ltd The machine adopts PLC programmable controller as its control core, completes the task of human-computer interaction through a touch screen, and also uses a high-precision rotary encoder to feedback the rotation amount to the control core in real-time to achieve precise control of the position [8].
Based on the above analysis, this article designs the overall plan based on the working model of the stone cutting robot, the worksite, and the load of the end tools. Including the design of the joint structure and transmission mechanism, as well as the structural design of the base, main arm, and arm, and draw the structural sketches of each part. Using ANSYS to carry out static analysis of the manipulator, analyze the force situation through the cloud chart, and determine whether it meets the design requirements. Kinematics analysis of the stone cutting robot.

2. Scheme Design of Stone Cutting Robot

2.1. Overall Design of Robot

The large heavy-duty stone cutting robot designed in this paper mainly processes stone plates, which can realize functions such as straight line cutting and curved arc walking, such as chamfering of stone plates, straight line trimming and arc trimming. The robot has a large working range and a heavy load on the end. In order to enable the robot to drive the processing head to any position in the movement space and meet the processing requirements, at the same time, the output bearing of the geared motor is not subject to large bending moments. After consideration, it was decided to put the gear motor at the joint of the robot arm vertically so that the output shaft of the gear motor and the ground are perpendicular to each other, and only provide the torque required for the relative rotation between the robot arm. The bending moment will act on the arm and base respectively. Since the reduction motor does not bear the bending moment of the large and small arms due to gravity, the arm length of the mechanical arm can be increased, thereby increasing the working space of the stone cutting robot. According to this, the construction form of the stone cutting robot studied in this paper is finally determined to be 3R1P, and its structural arrangement is shown in Figure 1.

Figure 1. The structure of the stone cutting robot.

2.2. Mechanical Structure Design of Main Arm

Figure 2 shows the assembly diagram of the main arm structure of the stone cutting robot. The first joint (the main arm rotating joint) adopts a combined drive scheme of motor and reducer. The main arm mechanical structure includes a base, a main arm, a main arm rotating shaft, and a servo motor main arm connecting plate, servo motor, RV reducer, thrust ball bearing, needle roller bearing, deep groove ball bearing, steel wire circlip for shaft, inner hole circlip, bearing washer. Among them, the servo motor 10 is fixedly connected to the upper part of the motor connection plate 11 by screws, and the lower part of the motor connection plate 11 is connected to the RV reducer 9, and the whole is fixed to the upper part of the base 1 by screws. On the arm 12, the main arm rotation shaft 2 is connected to the lower part of the base 1 and is fixed by screws, and the main arm 12 is installed on the main arm rotation shaft 2 and the base 1 through bearing matching so that it can rotate relative to them.
2.3. Mechanical Structure Design of the Arm

Figure 3 shows the assembly diagram of the arm structure of the stone cutting robot. The second joint (arm rotation joint) still uses the combined transmission method of the motor and the reducer, which is the same as the arm rotation joint (first joint). The transmission principle and structural design of the drive can simplify the structural design to a certain extent. The mechanical structure of the arm includes the arm, arm, arm rotation shaft, servo motor arm connection plate, servo motor, RV reducer, thrust ball bearing, needle bearing, deep groove ball bearing, steel wire retaining ring for shaft, inner hole circlip. Among them, the servo motor 9 is fixedly connected to the upper part of the motor connection plate 8 by screws, and the lower part of the motor connection plate 8 is connected to the RV reducer 10, and the whole is fixed to the upper part of the main arm 11 by screws, and the output end of the RV reducer 10 is connected to On the arm 5, the arm rotation shaft 1 is connected to the lower part of the arm 11 and fixed by screws, and the arm 5 is installed on the arm rotation shaft 1 and the arm 11 through a bearing so that it can rotate relative to them.

3. Static Analysis Based on ANSYS

In the design process, this subject uses ANSYS to perform static analysis of components, which can simplify the main arm and small arm into cantilever beams and analyze the stress and strain of the large and small arms. Through the stress-strain cloud diagram, find the stress concentration part, verify whether the structural strength of the main arm and the small arm meet the requirements, and optimize the part structure under the premise of meeting the design requirements. The material of the main arm and arm is gray cast iron HT300, and the material properties are shown in Table 1.
Table 1. Formatting sections, subsections and subsubsections.

| Elastic Modulus (MPa) | Poisson ratio | Mass Density (kg/m³) | Shear Modulus (MPa) | Tensile Strength (MPa) |
|-----------------------|---------------|----------------------|---------------------|-----------------------|
| 143000                | 0.27          | 7.30E+03             | 56.6                | 300                   |

According to the actual working conditions, set a cylindrical surface constraint at the right end of the main arm, as shown in Figure 4. In the upper part of the left end of the main arm, a surface load of 254.8 N is applied in the negative direction of the Z axis, and the lower part of the left end is applied a surface load of 3350 N in the negative direction of the Z axis, as shown in Figure 5.

After dividing the grid, click solve to get the stress distribution cloud diagram and deformation displacement cloud diagram of the main arm, as shown in Figure 6 and Figure 7, respectively. It can be seen from the cloud distribution diagram of the main arm stress in Figure 6 that the maximum stress of the main arm is 14.007 MPa, and the maximum stress occurs at the bearing installation part of the upper right part of the main arm. The maximum stress value of the main arm is much smaller than its tensile strength of 300 MPa, so it meets the design requirements. According to the cloud diagram of the deformation displacement of the main arm in Figure 7, under the maximum static load, the maximum deformation displacement of the main arm is 0.1037 mm, and the deformation displacement is small. When the maximum deformation displacement occurs, the influence on the accuracy of the robot's motion can be ignored, so it meets Design requirements. It can be seen from the cloud distribution diagram of the main arm stress in Figure 6 that the maximum stress of the main arm is 14.007 MPa, and the maximum stress occurs at the bearing installation of the upper part of the right end of the main arm.

4. Kinematics Analysis of Stone Cutting Robot

Model the coordinate system of the four joints of the stone cutting robot, as shown in Figure 8. In order to reduce the calculation complexity, the base coordinate system \( \{0\} \) and \( \{1\} \) are coincident. The D-H parameters of each joint of the stone cutting robot are shown in Table 2.

**Figure 4.** Main arm load constraints.

**Figure 5.** Definition of main arm loads.

**Figure 6.** Cloud stress distribution cloud diagram.

**Figure 7.** Main arm deformation displacement cloud diagram.
Using the parameters in Table 2, the transformation matrix of the four joints of the robot can be solved. Using these joint matrixes, the transformation matrix of the robot end coordinate system to the robot base coordinate system can be solved, that is, the positive kinematics equation of the stone cutting robot:

\[
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 \\
a_1 & a_2 & a_3 & a_4 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_3 \\
\alpha_4
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2 \\
a_3 \\
a_4
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix}
\begin{bmatrix}
d_1 \\
d_2 \\
d_3 \\
d_4
\end{bmatrix}
\]

Using the parameters in Table 2, the transformation matrix of the four joints of the robot can be solved. Using these joint matrixes, the transformation matrix of the robot end coordinate system to the robot base coordinate system can be solved, that is, the positive kinematics equation of the stone cutting robot:

\[
q_T = \begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 \\
a_1 & a_2 & a_3 & a_4 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_3 \\
\alpha_4
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2 \\
a_3 \\
a_4
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix}
\begin{bmatrix}
d_1 \\
d_2 \\
d_3 \\
d_4
\end{bmatrix}
\]

(1)

Therefore, according to formula 1, the inverse kinematics solutions of each joint of the stone cutting robot can be obtained. Since \( s\theta_2 = \pm \sqrt{1 - (c\theta_2)^2} \), it can be known that there are multiple solutions to the inverse kinematics solutions. The choice of multiple solutions should be determined according to the actual situation of the robot. Under the premise of avoiding collisions, the choice of multiple solutions is generally based on the principle of "shortest travel". In the experiment, the stones with different parameters were recorded in the table 3.

Table 3. Different parameters of stones in our experiment.

| Types of stone | Poisson ratio | Shear strength (MPa) | Tensile Strength (MPa) |
|---------------|--------------|----------------------|------------------------|
| Granite       | 0.1-0.3      | 20                   | 3-5                    |
| Rhyolite      | 0.1-0.25     | 10                   | 1-3                    |
| Limestone     | 0.1-0.25     | 17                   | 3-6                    |
5. Conclusion
This paper studies and designs a large heavy-duty stone cutting robot. According to the design requirements of the subject, the number of degrees of freedom of the stone cutting robot is determined to be 4, and the robot degrees of freedom are reasonably allocated according to the processing characteristics of the stone sheet. Therefore, the working space of the stone cutting robot is drawn by the control variable method and the geometric mapping method. Secondly, according to the overall design plan, the joint structure of the stone cutting robot is designed in detail, and the servo motors used for each joint are calculated and selected, and the ball screw at the joint of the third joint is also calculated. And selection. In order to verify the rationality of the design, this paper uses ANSYS to analyze the stress and strain of the big and small arms of the stone cutting robot, and sets the corresponding parameters in the software, such as the definition of material properties, constraints and loads, grid. According to the calculation and analysis of ANSYS software, the stress-strain cloud diagram of the main arm and arm is obtained. According to the stress-strain cloud diagram, the structural strength and stiffness of the main arm and arm meet the design requirements. Finally, the DH parameter method was used to establish the homogeneous transformation matrix between each joint of the robot and the coordinate system of the adjacent link of the robot, the positive kinematic equation of the stone cutting robot was derived, and the algebraic method was used. The inverse solution of the positive kinematics equation is verified, and the rationality of the model drawing is verified.

6. Future Research
We will research the working route of our proposed large heavy-load stone cutting robot including intelligent obstacle avoidance and stone cutting based on pattern design.

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