Design and Implementation of a New Climbing Robot for High Voltage Transmission Tower

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Abstract. A new type of high voltage transmission tower climbing tower robot is designed. Firstly, the structure of the transmission tower is analyzed to determine that the robot manipulator is a five-degree-of-freedom structure. Secondly, a manipulator capable of automatically positioning and tightening the angle steel surface was designed according to the L-shaped angle steel of the tower. The manipulator adopts electromagnetic absorption and grasping and tightening the angle steel. Thirdly, the theoretical calculation of climbing steps is carried out to determine the maximum step of the torsional climbing gait. Then STM32 SCM is used as a carrier to carry out various functional modules to achieve effective control of the robot's rotation, movement and positioning. Finally, the finite element simulation of the robot model was performed to analyze the deformation and stress of each component during the climbing process, and the rationality of the structure was verified. In addition, the experiment of tower climbing was carried out with the experiment iron tower in the outdoor. The results show that the robot manipulator is tightened and reliable, the weight bearing is large, the degree of freedom is not redundant, the climbing speed is fast, and the movement of obstacle crossing can be realized smoothly.

1. Introduction

In recent years, the power loss caused by accidents of high-voltage transmission towers has become increasingly serious. In order to reduce tower accidents, the power grid company regularly arranges artificial tower inspections. However, this detection method is inefficient and has a large potential safety hazard and is affected by the natural environment [1].

At present, a large number of researches on tower climbing robots have been carried out in China, and many representative robots have been designed [2-5]. Although the designed robot meets climbing requirements through theoretical simulation, there are many problems in the actual climbing process. For example, the lack of grasping force of the manipulator is easy to cause the slipping accident, the heavy weight of the complicated structure, the positioning accuracy is poor, the low efficiency of the climbing tower and poor obstacle avoidance.

In this paper, a five-degree-of-freedom self-reconfigured tower-climbing robot with simple

structure and fast and reliable design is designed. The advantage is that the manipulator uses an electromagnet to adsorb the L-shaped angle steel and tighten it with a hand, and the clamping force is great to prevent falling. Secondly, the self-reconfigurable structure method makes the structure simple and has little load and no redundant degree of freedom. Finally, a torsional climbing gait makes the stepping speed faster and the obstacles more advantageous.

2. Robot mechanism design

2.1. Field environment and requirements
The transmission line tower is made up of single equilateral L angle steel or combined L angle steel by electric welding or bolt connection. The main body of the tower is composed of four L-shaped angles of the main material. The connection between the oblique material and the main material is directly connected with bolts or a gusset plate method. The tower main material and the main material are directly connected via the outer L-shaped angle steel or the L-shaped angle steel plus the substrate. In addition, the cross arm and tower body are mainly connected with additional gusset plates.

The function of climbing obstacle can be achieved by crossing the L angle steel and bolts at the junction of the main material and the main material, the joint plate of the junction of the inclined material and the main material, and the vertical edge of the oblique material at the direct connection between the inclined material and the main material. As shown in Figure 1.
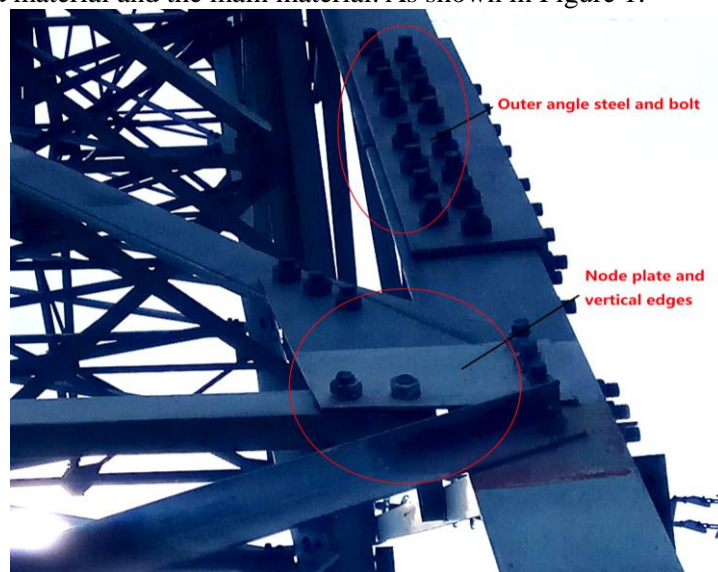

Figure 1. High-voltage transmission tower obstacles.

2.2. Robot Structure Design
The robot structure is designed to ensure that the robot can reach any position in the three-dimensional truss, and to meet climbing and obstacle avoidance functions. In addition, we must also ensure that the structure is simple, compact, flexible, and of low weight.

There are two feasible schemes to select the degree of freedom to meet the above features, including five degrees of freedom and six degrees of freedom [6]. According to the working environment of the robot, the symmetry of the structure and the difficulty of solving the inverse kinematics, the structure diagram of the robot is determined as shown in Figure 2 below.
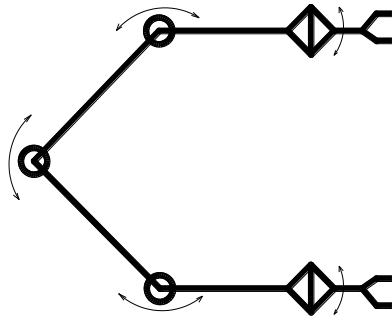
Figure 2. Robot structure diagram.

From the above figure, the robot structure consists of four arms and two manipulators, and there are five degrees of freedom. Figure 3 below shows a three-dimensional model of the robot.
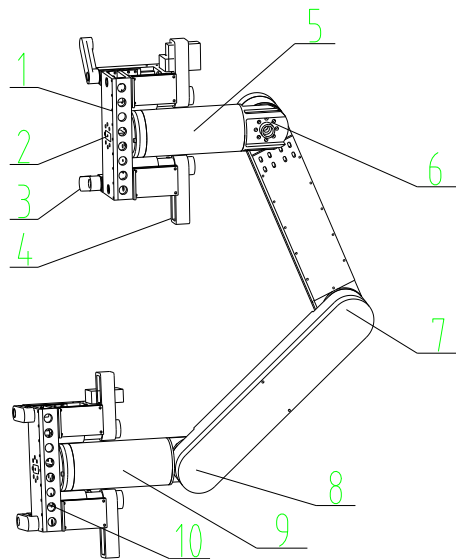

Figure 3. 3D model of robot (1. Manipulator 1 2. Photoelectric sensor 3. Hand grabbing 4. Ranging sensor 5. Shaft 1 6. Shaft2 7. Shaft 3 8. Shaft 4 9. Shaft 5 10. Manipulator 2).

As can be seen from the above figure, the end robot arm and the manipulator are connected by an I-joint module, and the robot arm is connected by an L-joint module. Each joint module is composed of a driving motor and a transmission mechanism, in which the motor provides power, and the transmission mechanism is used to change the torque of the power machine to meet the requirements of the working machine. By analyzing and calculating the output torque of each module joint of the robot, the transmission plan is determined as shown in Table 1.
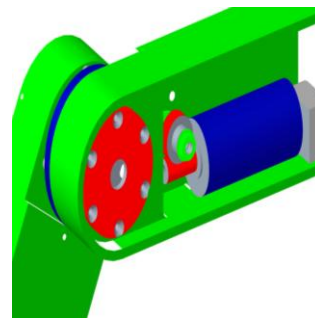
Table 1. Transmission scheme of joint module.

Module name	Motor model	Motor power	Primary transmission	Secondary transmission	Three-stage transmission
Type I	Maxon re25	200W	Planet gear (1:14)	Harmonic reducer (1: 80)	
Type L	Maxon re25	200W	Turbine worm (1: 120)	Timing belt (1:2)	Harmonic reducer (1: 80)

The above servo motors adopt the motor driver with the advantages of input pulse and direction signal for stepping mode control and high precision PWM signal speed control to ensure that each joint is an independent electromechanical system for convenient control. In addition, in order to achieve precise positioning and ensure motor rotation accuracy, the motor uses a line number of 100 encoders. Calculated from the above table, I joint module can achieve a 1:1120 reduction ratio, and the rotation accuracy is about 0.32 degrees. L module transmission ratio is 1:1280, its motor rotation accuracy is high, about 0.002 degrees. The structural models of I and L modules are shown in Figures 4 and 5 respectively.
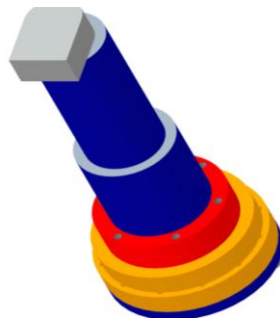
Figure 4. I joint module.   **Figure 5.** L joint module.

2.3. Manipulator Design

The effective design of the manipulator is the key to safe and reliable climbing of the crawler robot. The manipulator not only needs to be able to reliably grasp the L-shaped angle steel support robot, but also has an operating function, so its structure is more complicated [7-9]. In the process of robot climbing along the tower main material, only one robot grips the L-shaped angle steel in most cases. Therefore, on the one hand, the structural self-optimization is required to reduce the self-weight of the robot. On the other hand, the clamping mechanism must provide sufficient clamping force to ensure that the robot does not fall or slip during climbing. In addition, the robot must be able to accurately position the target angle to avoid erroneous operation.

To meet the above requirements, the manipulator model of climbing tower robot is designed as shown in Figure 6 below.
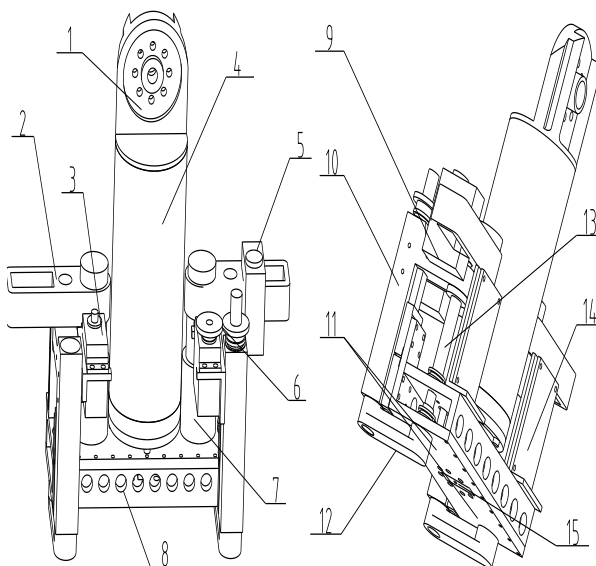
Figure 6. 3D model of manipulator (1. Flange plate 2. Equipped platform 3. Steering gear 4. I module shell 5. Fixed frame 6. Transmission gear 7. DC motor 8. Hollow structure 9. Ranging sensor 10. Moving rbar11. Robot underside 12. Hand grabbing 13. Screw 14. Power Supply 15. Photoelectric sensor).

2.3.1. Manipulator structure In this design, L-shaped angle steel with a length of 15cm and a thickness of 1.5cm is used as a tightening object for the manipulator. Through analyzing the characteristics of the L-angle steel, a gripping method of tightening the vertical face of the angle steel is adopted.

The manipulator adopts a rectangular hollow structure with long 17cm and wide 6.5cm, which not only reduces weight, but also has a large contact area between the lower surface and the angle steel vertical surface, thus increasing the friction force. In addition, in order to achieve the tightening action, each robot has a grip that has two degrees of freedom of rotation and vertical movement. The rotational freedom of the grip is controlled by the steering engine to ensure the rotation direction of the grip. The vertical degree of freedom of hand grasping is realized by a moving bar of hand grasping, a guide rail is arranged on the moving bar, and a slide block is arranged on the mechanical hand body,

and both constitute a guide rail slider mechanism. In addition, the nut fixed on the moving rod constitutes a ball screw drive with a screw having only one rotational degree of freedom installed on the manipulator. When the direct current motor drives the screw to rotate through the gear drive, the nut on the moving rod moves vertically relative to the screw. At this time, the hand grasping mounted on the moving bar moves up and down.

2.3.2. Manipulator positioning. The robot body is connected with the end of the I-joint module to achieve a 360-degree rotation in the horizontal direction, and is connected to the L joint module of the robot arm through the flange plate to ensure that it can realize the vertical direction swing. The robot body is connected to the I-joint module through the flange of the lower end of the I-joint module, and the servo motor provides the driving force to realize the 360-degree rotation of the robot. Secondly, the manipulator's swing is achieved by the rotation of the L-joint module. In addition, the manipulator reaches any position of the three-dimensional space through the rotational cooperation of each L-joint module and I-joint module.

As shown in Figure 3, the photoelectric sensor is installed at the center position of the bottom of the manipulator, and the two ranging sensors and cameras are arranged on the platform shown in 2 in Figure 4. The projection of the photoelectric sensor and the two ranging sensors on the bottom of the manipulator is collinear. When the manipulator 1 is moving, the manipulator 2 is always in a tightening state. When the manipulator moves to the target position, the photoelectric sensor on the manipulator 1 opens and detects, and the shaft 5 is rotated. When the photoelectric sensor fails to detect the angle steel, the shaft 5 stops rotating, which is the edge of the angle steel. Secondly, when rotating the shaft 1, when the distance sensor does not detect the angle steel, the point is the other edge of the angle steel. These two points ensure that the edge of the manipulator body is parallel to the edge of the angle steel. Then slowly rotate the shaft 5 so that the robot moves 3cm inward relative to the angle of the steel angle, and then rotate the shaft 2 so that the two ranging sensors measure the same distance to adjust the bottom surface of the manipulator to be parallel to the angle steel surface. Finally, rotate the shaft 3 slowly to contact the bottom surface of the manipulator and the angle steel surface. The servo is energized to rotate the grip to the lower surface of the angle steel, and the torque is provided by the DC motor, and the grip on the moving bar is driven to move upwards through the gear transmission and the ball screw transmission until the angle steel is tightened.

3. Robot climbing tower gait

From the above analysis of the working environment, we can see that in order to obtain a larger climbing step and effective obstacle avoidance effect, the robot uses the gait as shown in Figure 7 below.
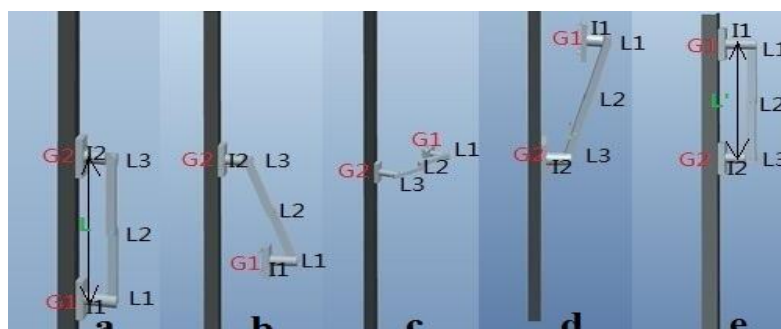
Figure 7. Climbing gait(G1 and G2 are manipulators, L1, L2, and L3 are transmission joints, and L and L' are gait lengths. a, b, c, d, e are climbing gaits).

The climbing process is as follows:

(a) In the initial position, G1 and G2 are clamped. G1 loosens slowly and G2 continues to clamp and supports the robot alone.

(b) L3 opens slowly, G1 moves outwards, leaving the bar completely to avoid interference with the

bar when the robot is twisting.

(c) When I2 is rotated 180 °, the robot is twisted for half a turn and re-aligned with the rod.

(d) L3 rotates in reverse until it returns to the initial angle.

(e) G1 clamps and the robot completes a climbing cycle. L' can be adjusted by controlling the angles of L1, L2, and L3.

When the robot adopts a twisting gait, the sequence is alternately switched. The distance of one movement cycle is: $0.78L < \Delta L < L$. The climbing step of this gait is larger than other gaits [10-11].

4. Control flow of robot

The design uses STM32 microcontroller to control the driver, motor, sensor, encoder and other modules [12]. The MCU sends the feedback signal to the upper computer through the wireless transmission module. The upper computer sends new instructions to the MCU to control the lower computer and completes the movement of the robotic system. The robot control flow is shown in Figure 8.
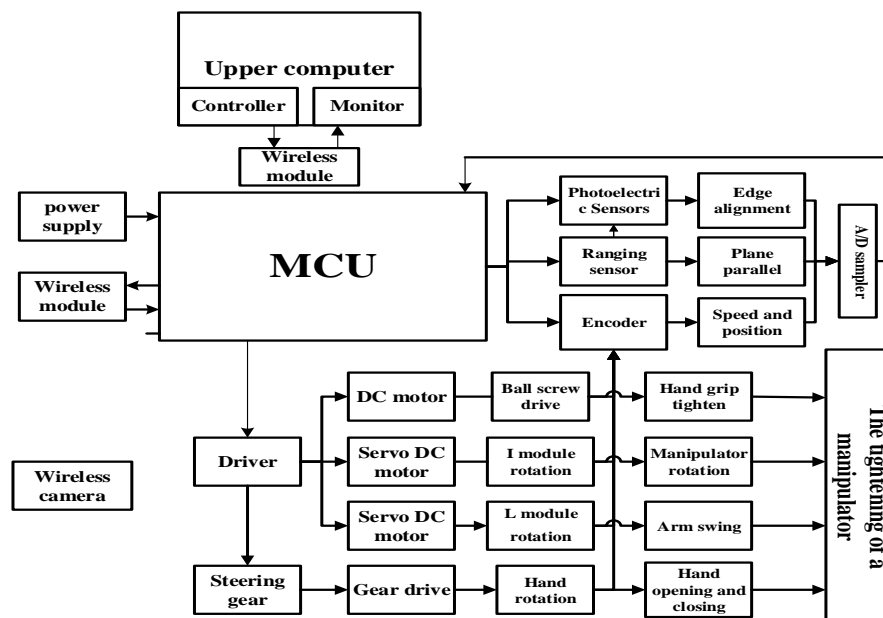
**Figure 8.** Robot control flow chart.

As illustrated in Figure 8, the power supply is powered by a single chip microcomputer, and both upper computer and MCU are equipped with wireless communication module. The upper computer monitor observes the climbing tower status of the robot in real time through the wireless camera, and the controller sends the instruction to the MCU through the wireless module. The MCU receives the instruction through the signal line and sends it to the motor driver, sensor and encoder. The encoder will detect the position and speed information of the motor and feed it back to the MCU in time. The MCU sends a new instruction command to the driver according to the feedback signal, and the driver can control the rotation speed and direction of the servo motor according to the received new instruction. Similarly, the photoelectric sensor and the distance measuring sensor begin to work after receiving the instruction from the single-chip microcomputer. During the work, the measurement data is continuously fed back to the single-chip microcomputer. The single-chip microcomputer judges according to the feedback signal and re-sends a new instruction to the sensor. The steering gear and DC motor on the manipulator are controlled by the driver which receives the single-chip instruction, without feedback link. In addition, the wireless camera communicates with the SCM through the wireless module. After the wireless camera sends the detected image signal to the SCM, the SCM sends the image signal to the upper computer monitor through the wireless module.

## 5. Structure simulation and prototype manufacture

5.1. Finite element analysis

In order to calculate the force and deformation of each gait in the climbing process of the robot, the ANSYS Workbench finite element analysis was performed on the deformation, strain and stress of each gait of the climbing tower [13]. The following figures 9, 10, 11 and 12 are simulated cloud charts for each step in the climbing cycle of the climbing tower robot.
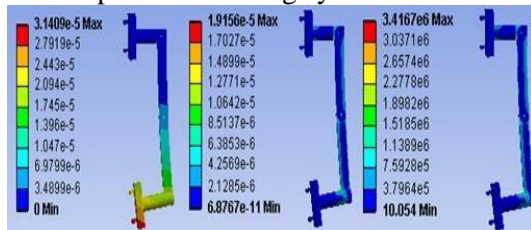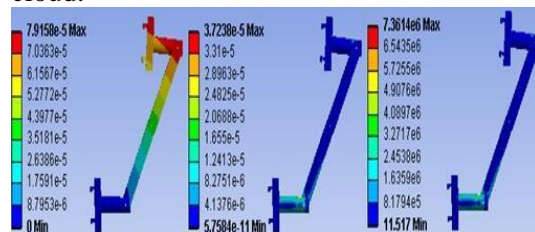

Figure 9. Gait a deformation, strain, stress cloud.
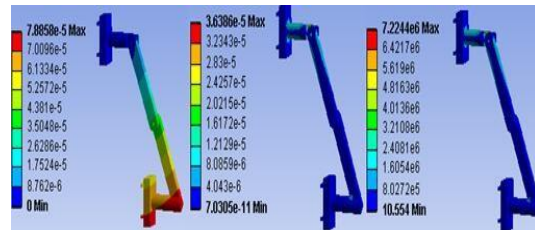
Figure 10. Gait b deformation, strain, stress cloud.
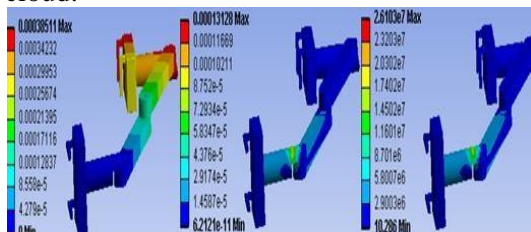
Figure 11. Gait c deformation, strain, stress cloud.

Figure 12. Gait d deformation, strain, stress cloud.

According to Figure 9, under the action of self-weight, the manipulator G1 is slightly deformed, strain and stress occur in both the manipulators and the joints, and the change is not obvious. Therefore, the manipulator G1 needs to be opened slowly to avoid large vibration deformation. It is known from figure 10 that when the mechanical arm starts, the manipulator G2 is slightly deformed under the self-weight, the maximum deformation is small, the strain and stress are mainly concentrated in the stress concentration parts. Therefore, the stress concentration phenomenon should be avoided as far as possible. As can be seen from Figure 11, when the arm is twisted by 90°, G2 tightens the angle steel to support the entire mechanical structure and the deformation of the end is large. Stress and strain are mainly concentrated in the L joint module. Therefore, the strength and rigidity of the material at the site should be strengthened, and the structural self-weight should be reduced. In addition, it can be found from the figure 11 that the maximum stress and strain values are small and are all within the design range. From Figure 12, when the mechanical arm is twisted by 180°, the manipulator G1 deforms within a certain range under its own weight, and the strain and stress are also concentrated at the L joint module, and the maximum stress and strain values are within the design range.

From the above analysis, it can be known that the deformation of the robot is mainly distributed on the suspended end manipulator, and the strain and stress are mainly concentrated on the rotating pair. Since the deformation amount, the stress and the strain are within the allowable range of the design, the structure of the robot is stable and reliable, and the climbing action can be completed. In addition, to ensure that the gravity of the robot itself is small, it is particularly important to ensure the reliability of each rotating pair and the stiffness and strength of the materials at each joint.

5.2. Prototype Experiment

In order to verify the operation of the robot under the actual working environment, the climbing ability of the tower-climbing robot was tested on the oblique material and the main material of the high-voltage transmission tower.

Firstly, the ability of the robot to climb the tower on the high voltage transmission tower is verified.

The two manipulator are tightened on the high voltage transmission tower, and the climbing experiment is carried out according to the gait described above. The climbing process is shown as shown in Figure 13 below.

Figure 13. Prototype experiment 1.

Secondly, in order to verify the climbing ability of the robot on the main material of the high voltage transmission tower, the experiment of the robot crawling along the main material of the tower is carried out. The process of climbing the tower is shown as shown in Figure 14 below.

Figure 14. Prototype experiment 2.

Through the above experiments, it is found that when the upper computer sends a movement instruction, the climbing robot can climb up along the L-shaped angle ridge line, indicating that this design scheme is feasible. When one end of the manipulator is tightened, it is enough to support the entire fuselage. The torsional climbing gait can effectively cross the tower obstacle. Through the above experiments, the upper computer can send the movement instructions, and the climbing robot can climb up along the L angle steel ridge line, which shows that the design plan is feasible. Experiments show that when the manipulator is tightened at one end, it is enough to support the entire fuselage and meet the load requirement. When the robot climbs the tower, each joint module rotates flexibly, and the manipulator can accurately tighten the surface of the angle steel, and the effect of twisting gait is better.

6. Conclusion

(1)The five-degree-of-freedom mechanical arm structure not only reduces its own weight, but also ensures that there is no redundancy in the degree of freedom.

(2)The manipulator achieves accurate positioning by means of photoelectric and distance measuring sensors. By gripping the angle steel to provide a larger clamping force, the manipulator can support the entire mechanical mechanism to maintain the balance of the robot after grasping the clamp.

(3)The torsional climbing gait step can effectively avoid the obstacles on the tower. In addition, the step is larger and the climbing speed is faster.

(4)Through the simulation analysis of each gait, the deformation of the robot is mainly concentrated in the end manipulator, and the stress and strain are mainly concentrated in the rotating pair and each joint. The values of the parameters meet the actual requirements. The simulation results show that under the premise of ensuring the robot's self-gravity, it is very important to ensure the reliability of each rotating pair and to strengthen the strength and rigidity of each joint.

(5)The prototype experimental results show that the robot can effectively complete climbing obstacles, verifying the rationality of robot design and the feasibility of climbing gaits.

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