Design of Negative Pressure Climbing Robot Based on Numerical Simulation

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Abstract. Aiming at the problem of low wall adsorption capacity of the wall-climbing robot, this paper designs a negative-pressure climbing wall tracing robot; the structure of the robot is designed, and a double-wheel differential control driving mode is determined; The key technical parameters are analyzed theoretically, and the calculation method of the minimum pressure difference and the minimum distance of the chassis from the ground is obtained. The numerical simulation of the negative pressure generator based on Fluent verified the rationality of the structure of the negative pressure generator. The distribution characteristics of the pressure in the negative pressure generator are displayed and analyzed. Finally, the physical model of the robot is built and the feasibility of the design is verified.

1. Introduction

Wall-climbing robots belong to special-type robots, sometimes called extreme-working robots, and their emergence has brought great convenience to the development of society [1]. At present, the work in the high-altitude environment and the extreme environment is mainly based on labor. This kind of manual operation is not only a problem of low efficiency and high cost, but also has great problems such as hidden dangers. The occurrence of casualties is also common [2, 3]. The design study of the wall-climbing robot will replace the manual work in high-altitude hazardous environments, greatly reducing the risk of high-risk operations. Not only can it improve work efficiency, but it can also generate certain social and economic benefits [4, 5].

Adsorption is a unique feature of wall-climbing robots and a major feature that distinguishes them from ordinary walking robots. At present, according to different adsorption methods, wall-climbing robots are generally classified into: negative pressure adsorption type, magnetic adsorption type, thrust adsorption type and biomimetic adsorption type [6, 7]. The University of Catania, Italy, developed the Alicia series of robots, which are vacuum-sucked by an intermediate suction chamber, and the two wheels are differentially driven by a separate motor. The robot weighs 4kg, has a slow walking speed, and has a load of 15kg, which can overcome obstacles of 1cm high. The Cromse combines an omnidirectional drive system with a complex adsorption system with seven chambers and a gas-filled rubber-filled skirt that fits the wall to maintain sufficient adsorption [8, 9]. It has a weight of about 50Kg and can carry a maximum load of 10Kg for inspection tasks of large concrete buildings. The NDT wall-climbing robot developed by South Bank University in London, UK, is used for inspection of weld seams [11, 12]. The main structure is two-stage articulation, which has a fast moving speed and good
obstacle-obstacle ability. The other is to connect the permanent magnets with the robot's motion mechanism. Such as the use of magnetic tracks or wheels [13]. The University of Coimbra in Spain has developed a new type of wall-climbing robot with high maneuverability that controls the speed of the three universal wheels for straight and turning motion. The robot can adapt to different curvatures and material walls, and is used to detect the defects of the ferromagnetic material surface and the convex arc surface structure [14].

In this paper, the wall-climbing robot is designed for the problem of low wall adsorption capacity of the wall-climbing robot. Two drive wheels are used to provide power and steering by providing a difference in rotational speed, and the sensor is used to detect the magnetic pole signal to track the robot. The physical model of the vertical state of the robot is established and mechanical analysis is carried out to obtain the calculation method of the minimum pressure difference of the robot on the wall. The fluid analysis of the negative pressure generator is carried out according to the Bernoulli equation, and the formula of the minimum distance of the robot from the ground is derived. The principle of the negative pressure generator was verified based on numerical simulation, and the pressure distribution in the negative pressure chamber was observed. Finally, the robot is demonstrated in kind to verify the rationality of the design.

2. Technical requirements

2.1. Workplace Requirements

The working position of the climbing wall robot is shown in Fig. 1. It consists of the originating area A, the navigation magnetic strip, and the finish line. The overall dimensions are: width 2000mm, height 1600mm, leg height 400mm. It is made of wood, white lacquered, and has a smooth surface. The smoothness is determined by the texture of the wood and the painting process. The navigation strip is black with a total length of 3640mm, a width of 50mm and a thickness of 1.2mm. It is made up of three arcs and straight lines, and the N pole faces outward and is attached to the wall. The originating area A is the area where the robot is placed, and the size is 300X300mm.

![Figure 1. Workplace of climbing robot](image-url)
2.2. Robot Technical Requirements

(1) The overall shape and width of the robot are not more than 300mm. If it is round, the diameter is not 300mm.

(2) The weight of the robot is not limited and the height is not limited.

(3) The robot must be autonomously operated and must not use any form of wired signal control or wireless signal control.

3. Overall design of the robot

3.1. Design of the Structure of the Climbing Wall Robot

The wall climbing robot mainly includes: a mechanical body, a driving system, a negative pressure generator, and a sensor module. The negative pressure generator is the core of the wall climbing robot, and the mechanical structure is the foundation. The overall structure of the wall climbing robot is shown in Fig. 2. The front DC motor is used to power both the drive wheels and to provide steering by providing a difference in speed. The rear universal wheel is used to assist steering. The brushless motor and the fan provide frontal pressure to the robot to attract the fan to the wall.

![Figure 2. Overall structure of the wall climbing robot](image)

3.2. Design of the Climbing Wall Control Scheme

The wall-climbing robot uses the single-chip microcomputer as the main control chip, and the robot adopts an independent control mode for walking, turning and generating negative pressure. The control principle is shown in Fig. 3. The magnetic induction sensor installed at the bottom of the robot detects whether there is a magnetic signal in the field, and transmits the signal to the DC motor control single-chip microcomputer. After receiving the signal of the magnetic induction sensor, the single-chip microcomputer sends a command to the motor driver to control the rotation speed of the left and right motors. There are three cases of sensor detection signals, and the conditions for controlling the motor movement are shown in Table 1.
Table 1. Robot tracking principle table

| Sensors name | Signal | Left and right drive wheel differential | Motion state |
|--------------|--------|----------------------------------------|--------------|
| Sensor 1     | No     |                                        | V_r=V_l      | Straight |
| Sensor 2     | Yes    |                                        | V_r>V_l      | Turn left |
| Sensor 3     | Ye     |                                        | V_r<V_l      | Turn right |
| Sensor 4     | No     |                                        |              |           |

Since the wall-climbing robot has to overcome its own gravity on the working wall, it is always necessary to provide an adsorption force during the working process. This adsorption force can be equivalently regarded as applying a positive pressure perpendicular to the wall surface to the robot, in order to generate static friction with the wall surface. If the frontal pressure is too large, the robot cannot advance, the frontal pressure is too small, and the robot will tip over. The gas pressure value in the adsorption chamber is controlled by the ESC module to control the rotation speed of the ducted fan, thereby ensuring the negative pressure in the adsorption chamber and realizing the adsorption function.

4. Determination of key parameters of the wall climbing robot

4.1. Determination of the Anti-Skid Condition of the Climbing Wall Robot
The robot is now placed horizontally on a vertical field for force analysis. The force analysis diagram is shown in Fig. 4. When the robot is placed vertically on a vertical plane, the robot will slide downward...
due to gravity. During the sliding process, the vertical field will give the robot a frictional force $f$. It is parallel to the contact surface and vertically upward. According to Fig. 4, the pressure $F_y$ of the robot against the wall and the support force $F_N$ of the wall facing the robot are a pair of forces and reaction forces. They are equal in size and opposite in direction. Therefore, if the robot is to be stationary on the wall, the friction $f$ should be greater than or equal to the robot's gravity $mg$. Set the sliding friction coefficient between the track and the wall to $\mu$. It can be obtained from the Newtonian mechanics formula:

$$f \geq Mg$$

$$\mu F_y \geq mg$$

Among them, $F_y$ is the pressure of the robot on the wall, which satisfies the relationship:

$$F_y = P_c \times S$$

Where $S$ is the contact area between the robot and the wall of the field, and $P_c$ is the pressure difference generated by the negative pressure generator. Then the condition that the robot does not slip on the wall of the site is:

$$P_c \geq \frac{mg}{\mu S}$$

**Figure 4.** Force analysis of the robot

4.2. Determination of the Height of the Robot Chassis
According to the Bernoulli equation, the relationship between the fluid pressure difference and the flow rate in the negative pressure generator is:

$$P_c + \rho gh + \frac{\rho v^2}{2} = C$$
Where $P_c$ is the pressure difference, $C$ is a constant, $\rho$ is the air density, and $v$ is the air flow rate. In an ideal state, the gravity of the air can be ignored, so that:

$$P_c + \frac{\rho v^2}{2} = C \quad (6)$$

According to the conservation of fluid energy:

$$P_1 + \frac{\rho v_1^2}{2} = P_2 + \frac{\rho v_2^2}{2} \quad (7)$$

Where $P_1$ is the outlet pressure of the negative pressure generator, $P_2$ is the inlet pressure of the negative pressure generator, $v_1$ is the outlet speed of the negative pressure generator, and $v_2$ is the outlet speed of the negative pressure generator. We can get:

$$P_1 - P_2 = P_c = \frac{\rho (v_2^2 - v_1^2)}{2} \quad (8)$$

$$Q = S \times v_2 \quad (9)$$

$$S = d \times L \quad (10)$$

Where $Q$ is the flow rate, $S$ is the inlet area of the negative pressure generator, $L$ is the circumference of the robot chassis, and $d$ is the distance from the chassis to the site. The above formula is synthesized:

$$d \leq \frac{Q}{L} \sqrt{\frac{Q^2}{2P_c + \rho v_1^2}} \quad (11)$$

5. Numerical simulation of negative pressure generator

5.1. Pre-Processing of the Model

The numerical simulation method is to use a computer to do experiments, and the discrete solutions in the fluid region can be obtained quickly when given boundary conditions and governing equations. In the experiment, the model is simplified. As shown in Fig. 5, the fluid domain model of the negative pressure generator is obtained by ignoring the tires, DC motor, fan and other parts. The fluid and model include three parts: speed inlet, wall and speed outlet. In order to facilitate the display of the later results, a three-dimensional coordinate system is established with the left front of the robot as the origin. The model is divided into grids, and 2,827,314 grids are obtained, with a total of 477,653 nodes. To ensure the accuracy of the calculation results, the grid of speed entries is encrypted.
In order to keep the simulated conditions consistent with the actual conditions, while saving the calculation time and cost, this paper makes the following assumptions on the model before the numerical calculation: the wall has no slip assumption; the wind speed of the boundary wall of the simulated area is 0. Assume that the velocity and direction of the air inlet remain the same; ignore the gravity of the air itself and treat the gas as an incompressible gas.

5.2. Results and Analysis of Numerical Simulation

In this experiment, the type of speed exit is set to "velovity-inlet", the size is -240m/s, the type of speed entry is set to "outflow", and the type of wall is set to "wall". After the experiment is finished, x=55mm is selected as the observation plane, and the pressure cloud diagram of the negative pressure generator on this plane is obtained, as shown in Fig. 6. It can be seen in the cloud diagram that due to the increase in the air flow rate of the negative pressure generator, the internal pressure is less than the standard atmospheric pressure, and the internal pressure distribution is uniform. There is no complicated turbulence condition here, which satisfies the principle of the negative pressure generator. The line where the points (55mm, 0mm, 70mm) and points (55mm, 90mm, 70mm) are located is the monitoring point of the pressure, and the change of pressure along the y-axis is observed. The observation results are shown in Fig. 7, and it can be seen that the magnitude of the pressure gradually becomes smaller as the direction of the y-axis.

![Pressure cloud diagram of x=55m plane](image6)

**Figure 6.** Pressure cloud diagram of x=55m plane

![Curve of pressure change](image7)

**Figure 7.** Curve of pressure change
Five planes were selected every 40 mm on the z-axis as the observation surface, and the change of the pressure on the z-axis was observed. It can be observed that the pressure along the z-axis changes smoothly, and the isobar line distribution becomes more and more sparse. As shown in Fig. 8.

![Pressure cloud pictures of different planes](image)

**Figure 8.** Pressure cloud pictures of different planes

6. Test verification of wall climbing robot

6.1. Selection of the Main Control Chip

This experiment selects STC89C52 as the main control chip. It is a low-power, high-performance CMOS 8-bit microcontroller with 8K in-system programmable flash memory. On a single chip, with a smart 8-bit CPU and in-system programmable Flash, the STC89C52 provides a highly flexible, ultra-efficient solution for many embedded control applications. Fig.9 is a physical diagram of the minimum system of the microcontroller, and Fig. 10 is a diagram of the chip package.

![MCU minimum system](image)

**Figure 9.** MCU minimum system

![Chip package diagram](image)

**Figure 10.** Chip package diagram

6.2. Verification of Robot Adsorption Capacity and Tracking Ability

All the parts used are installed to obtain the robot object, placed on the prepared site, the robot can be attached to the wall without sliding, and can be straight, left and right according to the magnetic strip. The verification results are shown in the Fig.11, where (a) is the straight-through diagram of the climbing wall robot, where (b) is the left-turning diagram of the climbing wall robot, and (c) is the right-turning diagram of the climbing wall robot.
7. Conclusion
This paper designs the climbing wall tracking robot. The structure of the robot was designed using two drive wheels to provide power and steering by providing a difference in rotational speed, and the sensor was used to detect the magnetic pole signals to track the robot. The control scheme of the robot tracing wall is determined. The physical model of the vertical state of the robot is established and the mechanical analysis is carried out. It is concluded that the pressure difference is the key factor affecting the adsorption capacity of the robot, and the calculation method for calculating the minimum pressure difference is derived based on the mechanical model. The fluid analysis of the negative pressure generator is carried out according to the Bernoulli equation, and the formula of the minimum distance of the robot from the ground is derived. Based on the numerical simulation, the principle of the negative pressure generator is verified, and the pressure distribution in the negative pressure chamber is observed, and the conclusion that the pressure gradually decreases along the direction of the y-axis. Finally, the robot is demonstrated in kind to verify the rationality of the design.

Acknowledgments
Chengliang Zhang is the corresponding author of this paper. This work was financially supported in part by Shandong Province Natural Science Foundation, China under Grant ZR2019MEE113, and in part by Shandong Provincial Key Research and Development Plan of China under Grant 2018CXGC0908 and 2017CXGC0215, and in part by Shandong Provincial Major Agricultural Application Technology Innovation Projects of China under Grant SD2019NJ012, and in part by the Shandong Province Agricultural Machinery Equipment Research and Development Innovation Plan Project under Grant 2017YF047.

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