Design of a Vacuum Adsorption Wall Climbing Robot

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Abstract. In this paper, a new type of wall climbing robot with multi vacuum suckers is developed. The robot structure and working principle are introduced in detail. The analysis of safe adsorption force of the wall climbing robot. The mechanical model of the suckers is established. The adsorption force of the suckers is determined based on the experiments. The robot prototype is made. And a large number of experiments are carried out to verify the feasibility of the wall climbing robot. The results show that the prototype can walk on the vertical wall of various materials. The experiment results of the prototype walking on the vertical steel plate surface show that the maximum load is 13kg. And can span 20x8mm cracks.

Introduction

At present, the manual high-altitude operation exists in all walks of life. The manual high-altitude operation has many disadvantages such as high-risk factors, high labor intensity, and low efficiency [1]. This requires an automated device instead of manual work. Therefore, many scholars have conducted extensive research on wall climbing robots and achieved remarkable results.

The main methods of wall climbing robot adsorption include magnetic adsorption type, biomimetic adsorption type, mechanical holding type, negative pressure adsorption type, etc. The magnetic adsorption wall climbing robot [2,3] can only adapt to the magnetic wall. Although the bionic adsorption wall climbing robot [4,5] can adapt to the non-magnetic wall surface, the absorption force on the wall surface is small. The mechanical clamping wall climbing robot [6,7] can only be used in special shapes. The negative pressure adsorption wall climbing robot [8,9] can adapt to different material walls.

This paper describes a wall climbing robot that uses multi vacuum suckers to absorb. The wall climbing robot can safely move on a variety of wall surfaces, and the wall climbing robot can walk on a cracked wall.

The rest of this paper is organized as follows. Section II analyzes the safe adsorption force of robot. Section III introduces the mechanical structure of the vacuum adsorption wall climbing robot. Section IV gives the force analysis and experiment of the suckers. Section V presents the robot prototype and experiments, and finally section VI draws the conclusion.

Mechanical Structure

The three-dimensional model of the vacuum adsorption wall climbing robot, is shown in Figure 1 (a) & (b). The climbing robot is mainly composed of a moving mechanism, main body, and an adsorption device. The robot uses vacuum adsorption to adapt to the wall of different materials. The moving
mechanism adopts wheeled movement, which has better motion continuity, simple mechanism, and simple control.

The adsorption device is mainly composed of a vacuum sucker and a vacuum generator. The vacuum generator is connected in series by a connection of a pipe joint and a vacuum gas pipe. The vacuum tube is ventilated, and the vacuum generator sucks out the gas in the vacuum sucker to generate a certain negative pressure in the vacuum sucker. The wheels on each side are connected by a timing belt, and each wheel is a drive wheel. Two DC servo motors are arranged diagonally front and rear, each motor drives two wheels on each side. The robot steering is achieved by differential control of the two motors.

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Safety Adsorption Analysis

The slippage of the wheel and the wall is the main form of the instability of the wall climbing robot on the vertical wall. When the adsorption force acting on the moving wheel is too small, the dynamic friction generated by the wheel and the wall surface is insufficient to drive the wall climbing robot to move forward, and the slip between the wheel and the wall may occur. In order to ensure the normal movement of the robot, a safe adsorption force is required.

When the wall climbing robot adsorbs on the vertical wall with the attitude angle $\theta$ and moves forward along the $Y_o$ axis, the mechanical model of the wall climbing robot is shown in Figure 2:

To simplify the force model, the force between the vacuum sucker and the wall is concentrated on the center of the sucker. $N_i$ is the support for the wall of the vacuum sucker. $F_{fr}$ is the friction between the vacuum sucker and the wall. $F_{pa}$ is the adsorption force of the vacuum sucker on the body. $F_{dl}$ is the effect of the vacuum sucker on the lip of the sucker. $G$ is the gravity of the robot. $H$ is the...
distance from the center of gravity of the robot. \( N_j \) is supportive of the wall to the wheel. \( F_j \) is the friction between the wheel and the wall.

When the wall climbing robot goes straight along, the condition that the wheel does not slip should satisfy the following Equation.

\[
\sum_{j=1}^{m} F_j + Ma - \sum_{i=1}^{n} F_{ji} - G\cos \theta \geq 0
\]  

(1)

\( a \) is the acceleration of the robot. \( M \) is the quality of the robot. According to the calculation Equation of dynamic friction.

\[
\begin{align*}
\sum_{j=1}^{m} F_j &= \sum_{j=1}^{m} N_j \mu_{ll} \\
\sum_{i=1}^{n} F_{ji} &= \sum_{i=1}^{n} N_{ei} \mu_{ee}
\end{align*}
\]  

(2)

The sliding friction coefficient between the suckers and the wall surface in the above Equation is \( \mu_{ee} \). The coefficient of sliding friction between the wheel and the wall is \( \mu_{ll} \).

\[
\sum_{j=1}^{m} N_{ji} \mu_{ll} + Ma - \sum_{i=1}^{n} N_{ei} \mu_{ee} - G\cos \theta > 0
\]  

(3)

The ratio of the adsorption force acting on the lip of the vacuum sucker to the adsorption force acting on the body of the wall climbing robot is defined as \( \lambda \).

\[
\sum_{j=1}^{m} N_j - \sum_{i=1}^{n} F_{pi} = 0
\]  

(4)

\[
F_{pi} = N_{ei} = \lambda F_{pi}
\]  

(5)

According to Equation (3), (4), (5), the adsorption force acting on the robot wheel should satisfy the following Equation.

\[
\sum_{i=1}^{n} F_{pi} \geq \frac{G\cos \theta - Ma}{(\mu_{ll} - \lambda \mu_{ee})}
\]  

(6)

**Force Analysis and Experiment of the Suckers**

In the previous section, the phenomenon of robot wheel slippage was analyzed, and the minimum adsorption force required for the robot wheel to not slip was obtained. The vacuum adsorption wall climbing robot designed in this article, its adsorption force is provided by vacuum suckers. Therefore, it is necessary to analyze the vacuum suckers and use it as the basis for selecting the suction force of the suckers.

The sucker used in this paper is a commercial short corrugated tube vacuum sucker. The mechanical model of the sucker in different states is shown in Figure 3.
The weight of the sucker is $G$. The horizontal pull is $F$. The friction between the sucker and the wall is $F_f$. The support of the wall facing the lip of the suckers is $N_q$. The vertical tension is $F_v$. The force of the adsorption force on the lip of the suckers is $F_{pp}$. The forces acting on the suckers after the deformation occurs is $F_t$.

The sucker is in the static equilibrium state of (b), it can be obtained according to the balance condition.

$$
\begin{align*}
F_x + F_{pp} - N_q - F_s &= 0 \\
F_v + F_f - G &= 0
\end{align*}
$$

(7)

The sucker is in the motion balance state of (c), it can be obtained according to the balance condition.

$$
\begin{align*}
F_x + F_{pp} - N_q - F_s &= 0 \\
F_v - F_f - G &= 0
\end{align*}
$$

(8)

Due to $F_{pp} = N_q$, According to Equation (1) & (2) can be obtained.

$$
F_t = F_s
$$

(9)

The sucker is deformed by the adsorption force $F_t$ from the initial non-adsorbed state. The shape variable is $H - H_1$. As the adsorption force increases, the horizontal tension $F_v$ increases to maintain the shape variable of the suckers $H - H_1$. From the above analysis shows that:

$$
F = F_t + F_{pp} + F_s
$$

(10)

The total adsorption force generated by the sucker is $F$. According to Equation (3) & (4) can be obtained:

$$
F = F_t + F_{pp} + F_s
$$

(11)

The Equation for calculating the total adsorption force generated by the sucker is as follows.

$$
F = \Delta P \times S_s
$$

(12)

The pressure difference between the inside and outside of the sucker is $\Delta P$. The effective adsorption area of the sucker is $S_s$. 

Figure 3. Vacuum sucker adsorption force analysis: (a) No adsorption state, (b) Static equilibrium, (c) Sliding upward motion.
When the sucker is mounted on the wall climbing robot body, the horizontal force \( F_x \) can be provided by the wall climbing robot body. Therefore, the adsorption force acting on the robot body is \( F_x \).

\[
F_x = F_x = F - F_s - F_{pp}
\]  

(13)

The above analysis and Equation (4) show that the suction force of the vacuum sucker on the moving wheel is smaller than the total suction force of the vacuum sucker.

The Experiment of the Suckers

It is known from the force analysis of a single sucker. The suction produced by a single sucker is applied to the body of the robot, to the lip of the sucker, and the deformation of the sucker. There is a certain proportional relationship between these three forces, and the selection of the suction force of the vacuum sucker is affected. Therefore, the next experiment is used to explore the relationship between these three forces.

This experiment adopted indirect measurement. Vacuum negative pressure gauge measures the pressure inside of the vacuum sucker. According to Equation (11), the total adsorption force generated by the vacuum sucker can be obtained. The position where the sucker is in contact with the wall surface without deformation. The vacuum negative pressure measured when the cage is in contact with the wall surface to generate support force. The adsorption force acting on the suction disc deformation can also be obtained, according to the Equation (11). The total suction force of the suckers minus the suction force required for the deformation of the sucker. The adsorption force acting on the lip of the suckers can be obtained.

The experimental instruments used in this experiment is a lip vacuum suckers with a diameter of 80mm. The electronic scale has a measuring range of 40 kg and an accuracy of 10 g. The digital display vacuum gauge with a range of [-100kpa, +100kpa]. And an accuracy of 0.1. The experiment setup is showed in Figure 4.

According to the experimental data, the relationship between the adsorption force ratio of the sucker deformation and the vacuum pressure and support force is obtained through Matlab simulation, as shown in Figure 5 (a). The relationship between the adsorption force acting on the lip of the sucker and the vacuum pressure and the supporting force, as shown in Figure 5 (b). The relationship between the ratio of adsorption force on the body and vacuum pressure and support force, as shown in Figure 5 (c). The relationship between the support factor and the vacuum pressure and support force, as shown in Figure 5 (d).
According to the above experimental data simulation diagram: (1) There is a certain proportional relationship between these three forces. (2) The ratio of the adsorption force of the suckers on the wheel to the total adsorption force generated by the sucker decreases with the increase of the vacuum pressure and the deformation of the sucker. (3) When calculating the minimum adsorption force, refer to the value of (d) graph $\lambda$ to obtain a more accurate minimum. (4) When calculating the total adsorption force of the vacuum sucker for selection, refer to the ratio of (c) adsorption force value.

Prototype and Experiments

Based on the mechanical design, the prototype of the robot is made, as shown in Fig 6 (a). The weight of robot is 11.5Kg. The overall size of the robot is 550×520×20mm.
Walking on Different Walls

The robot prototype is tested on different walls to test the absorption and adaptability to the different surfaces, shown in Figure 6 (b) & (c) & (d). The walls of the experiment were laboratory hand-drawn facades, laboratory wall surfaces, and vertical steel plate walls. The laboratory hand-painted facade material is stainless steel, and the wall brush has a smooth paint surface. The laboratory wall surface with a putty, rough surface. The surface of the steel plate wall is divided into rust and rust-free areas, the area with rust is rough, and the area without rust is smooth.

Capabilities Across Cracks and Payload Capacity

The robot performs load capacity tests on a vertical steel plate. As shown in the figure 7 (a) & (b) & (c), the robot walks to the left at a certain slope in the area with a smooth steel plate without loaded. The crack size is 20×8mm. During the experiment, the robot moves smoothly and smoothly pass through the crack. As shown in the figure 7 (d) & (e) & (f), the robot walks upward at a speed of 12m/min with a load of 13kg in a smooth area on the steel plate. The robot does not have the phenomenon of wheel slip, overturning and al.

Conclusion

This paper introduces a new kind of wall climbing robot with multi suckers. The mechanical model of a vacuum sucker is established. The suction force analysis experiment was carried out to determine the suction force of the suckers. Develop prototypes and carry out adsorption walking on different walls, with load walking, crossing cracks, and other experiments. A series of experiments on the prototype showed the feasibility of the suction mode of the vacuum sucker. In the future, robots will be equipped with devices such as inspection and cleaning.

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