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Mechanism Design and Mechanical Analysis of Multi-Suction Sliding Cleaning Robot Used in Glass Curtain Wall

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In order to meet the needs of high-altitude glass curtain wall cleaning, a multi-suction sliding cleaning robot was designed. The sliding robot sucker, cleaning system, obstacle avoidance and rotation ability, walking circuit and mobile working principle of the cleaning robot were designed. This involved the analysis of the robot's anti-rollover mechanics during adsorption, of robotic winds when working at height, and of anti-sliding mechanics during robot movement, in order to explore feasible ways to improve the robot's adsorption performance. The relationship between the effective diameter D of the suction cup, the vacuum degree Δ P, and the gravity G should be determined by the anti-slipping analysis. In order to ensure the safe and reliable adsorption force and the flexibility of this robot when moving on a wall, the aforementioned analyses were conducted to improve the motion performance of wall-climbing robots, which provides a good theoretical basis for design optimization and motion control of cleaning robots. The curtain wall cleaning robot has stable walking ability and can clean the wall surface effectively; therefore, it has a certain practical value.

Keywords: Curtain wall cleaning robot, Multi-suction cup sliding type, Mechanical analysis, Institutional design

1. INTRODUCTION

Glass curtain walls have been widely used in high-rise buildings as a structure to protect the exterior of buildings. They have the advantages of providing good lighting, good thermal insulation and moisture-proof performance, practical appearance and so on. [1] Due to the constant wind and sun, glass curtain walls need to be cleaned and maintained regularly, but traditional manual cleaning methods are inefficient and dangerous for high-altitude operations. Therefore, the use of wall-climbing robots instead of manual cleaning methods for the cleaning of curtain walls has become a hot topic at home and abroad. [2] The development of artificial intelligence makes it possible for robots to perform dangerous work, instead of humans. The building industry is currently one of the industries with the lowest level of mechanization; hence, the emergence of robots signals a trend for its future development.

The cleaning robot was first developed by the Russian Academy of Mechanical Sciences. It is a simple, wall-climbing robot with a single suction cup structure. The suction cup consists of a moving mechanism, a cleaning operation device and a control unit. [3] It must have three functions of adsorption, movement and cleaning in order to move on the glass surface and complete the cleaning function. In addition, it needs a communication system to facilitate remote control. At present, the cleaning technology comprises physical cleaning, chemical cleaning or microbiological cleaning in accordance with the differences in the working principles. [4] Chemical cleaning and microbial cleaning are not widely used because of cost and environmental factors.

Considering the costs and convenience of operation, only the mechanical cleaning methods in the physical cleaning method category have become popular. Adsorption capacity refers to the ability of a robot to park on the surface of a glass structure with some driving force without falling down due to gravity. Kim Hyun-Kyo University scholars Kim, Taegyun and Kim, Jongwon proposed that curtain wall cleaning robots can maintain the contact force between the cleaning unit and various types of walls to ensure good cleaning performance, for which they proposed a tracking solution based on position impedance control for moving, wall-climbing cleaning devices. [5] Usually, the adsorption method can be categorised as negative pressure adsorption, magnetic adsorption, gas thrust adsorption, special adsorption and so on. All of the pressure adsorption type have few requirements in terms of wall surface materials and are widely used. Mobile function refers to a robot's ability to overcome obstacles while cleaning the glass surface, and being able to move according to a specific trajectory, thereby broadening the cleaning scope. Zhao Qichao introduced the Kalman filter algorithm to process the distance information for the window frame obstacle detected by a double ultrasonic wave, thus obtaining more accurate obstacle distance information. [6] The cleaning robot can be wheel type, cross frame type, crawler type or step foot type according to the movement mode. The attachment method and the movement method allow formany combinations. The utility and application scope of various combinations are all different. Moreover, it is worth noting that when cleaning robots are working at heights, they are inevitably affected by high-altitude wind loads, which can cause vibration and affect the stability of the robot's movement. To address this problem, Hong, Daehie, Moon, and Sung-Min proposed a method of state estimation that takes into account the dynamic characteristics of the wire rope in order to control and suppress vibrations. [7]

This study uses a multiple suction cup, negative pressure suction, sliding cleaning robot, because there is no redundancy for the single suction cup, and the wall surface must be high. And when the robot moves, there is sliding between the sealing device and the wall surface, which is easy to wear. When the robot encounters a window frame or groove, if the sealing device is not reliable, the vacuum degree is difficult to maintain, thereby jeopardizing safety. [8] The multi-suction vacuum suction type has addressed this problem.

In addition, the use of sliding seal suction cups facilitates continuous motion, and due to the higher degree of vacuum inside the suction cup, it is beneficial to reduce the overall size and weight of the robot, which is critical for wall robots. This will be explained in greater detail in the following analysis of the anti-overturning force during robot adsorption.

2. DESIGN OF SLIDE GLASS WALL CLEANING ROBOT MECHANISM

The cleaning robot comprises sucker negative pressure suction, moving wheels, a water spray system and a cleansing device.

2.1 Sliding Suction Cup Design

The sliding suction cup consists of an electric fan and a sliding seal device, and has the advantages of being insensitive to gas leakage, of having a relatively simple structure, and not requiring large-scale air pump equipment, and is more suitable for cleaning a smooth wall surface. When the drive motor is running and each suction cup is flat and close to the wall surface, negative pressure is generated in the suction cup, and the robot is adsorbed on the wall surface under the action of the sealing device, thereby maintaining the pressure of the scraper against the wall surface and the pumping force of the brush rotating at high speed on the wall surface.

When designing the suction cup, special attention should be paid to the setting of the adsorption force value, neither too large nor too small. Due to the relative sliding between the sliding suction cup and the wall surface, the greater the adsorption force will increase the positive pressure, the sliding friction resistance and the rolling friction resistance of the wheel of the sliding suction cup contact sealing surface to be overcome during the movement of the wall surface robot will increase. It is possible to make the wheel wall robot unable to move and it is necessary to increase the driving power; otherwise, the motor may be overloaded or burned. However, if the adsorption force is too low, the robot's own gravity cannot ensure the stable adsorption of the wheel wall robot during movement; even if the wall adsorption is maintained, the driving wheel cannot fully contact the wall surface because of a too small deformation of the sealing device. Even if left unconnected, it cannot obtain sufficient wall traction.

2.2 Cleaning System Design

The cleaning system of the cleaning robot includes three parts of a spray system, a washing device and a cleaning device, that is, scrapers. The cleaning method uses a combination of a rotary brush and a scraper. Considering that the object to be cleaned is glass, it is necessary to wipe off the water after cleaning. Otherwise, it will leave traces that obscure the glass and affect its appearance, and the robot's own wheels will also slip easily when it encounters water. Therefore, wiper plates are installed on the front and rear sides of the robot.

The cleaning is done using mechanical force. The rotating brush is rotated by the motor, and the flexible cleaning material on the rotating brush continuously hits the surface of the curtain wall to accomplish the cleaning. In the past, cleaning-robots research at home and abroad on mostly used pneumatic brushing or continuous scrubbing methods. Pneumatic methods had the disadvantages of low operating frequency and the need for complicated ancillary equipment, which not only increased the overall size and weight of the robot, but also caused the scrubbing method to consume more water. The brush cleaning method solves the above problems well, and the dirt on the curtain wall can be effectively removed to meet the actual operation requirements using a simple device.

2.3 Obstacle and Rotation Capability Design

Because the curtain wall has frames which are either obvious or hidden, the cleaning robot must have a good ability to overcome obstacles when walking on the surface. The design idea for tackling obstacles originated from the combination of two basic modules. These are fixed on the same platform and driven by push rods and guide rails so that they can move vertically up and down the platform to avoid obstacles. When the lower module is adsorbed on the glass curtain wall, the lower push rod is pushed

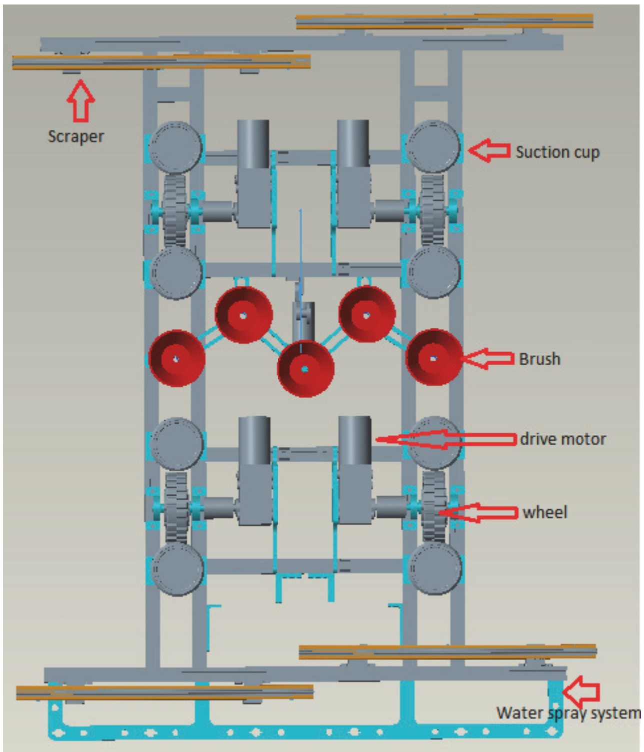

Figure 1 Structure of multi-suction chuck sliding cleaning robot.

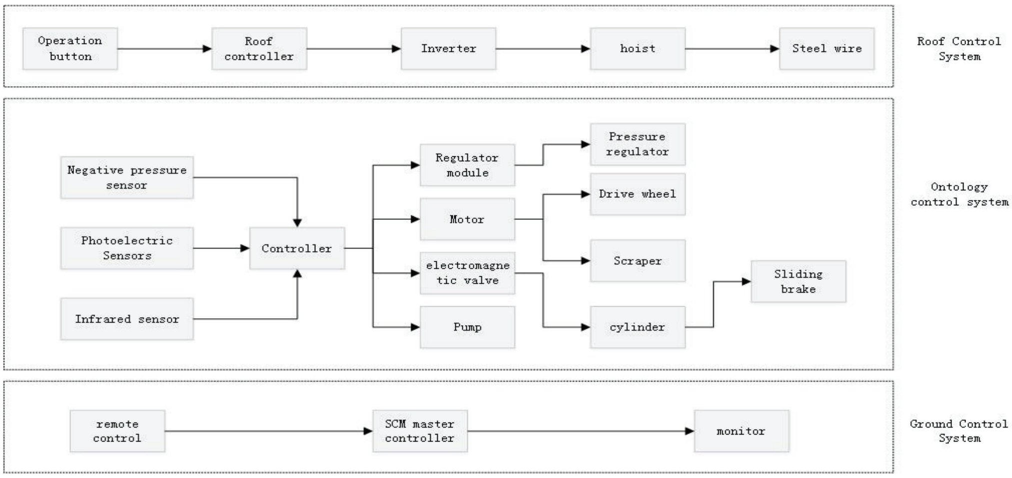

Figure 2 Machine control system.

out, the upper module is suspended, and the entire module can be driven up and down by the dual motors of the lower module. Similarly, when the upper module is adsorbed on the glass curtain wall, the upper push rod is pushed out, and the lower module is in a suspended state, and relies on the dual motors of the upper module to drive the entire robot up and down. In order to reduce the 'blind' cleaning area, the robot needs to increase its own rotation function so that it can stop at any angle and utilize a variety of cleaning devices so that the surface can be cleaned at any angle and the blind area of curtain wall cleaning can be reduced.

2.4 Walking Circuit Design

The robot circuit comprises a STM32 micro controller as a main control chip, a MOS tube drive module, a motor drive module, a relay module, a wireless module, a GPS module, and a pressure sensor. The machine control system is shown in Figure 2.2.

2.5 Mobile Working Principle of Cleaning Robot

The robot consists mainly of eight sucker vacuum suction devices, traveling devices, high-pressure spray cleaning devices, ducted fans, and cleaning mechanisms. The sucker system has eight single-sided circular arc suction cups, an oval negative pressure chamber and a sealing device. When the ducted blower operates, eight suction cups are flat against the wall surface, negative pressure is generated in the suction cup under the effect of the sealing device, and the robot is adsorbed on the wall surface, thereby resisting the pressure on the wall surface when the cleaning device is scraping it. During the cleaning process when the robot moves from the top to the bottom, due to the relative sliding between the suction cup and the wall surface, the adsorption force is not as strong as possible. If the adsorption force is too large, the robot cannot slide smoothly. However, if the adsorption force is too low, the robot cannot reliably adsorb to the wall when the sucker encounters excessive gas leakage from a recess in the wall surface, or has poor adaptation to wall surfaces. In addition, during the operation process, if the cleaning pressure acting on the wall is too low, the cleaning quality cannot be guaranteed. But, when the cleaning pressure is too high, the reaction force of the wall facing the robot is also high; therefore, the adsorption force should increase to prevent the robot from falling.

3. MECHANICAL ANALYSIS OF CLEANING ROBOT

3.1 Mechanical Analysis of Adsorption

(1) Anti-Overturning

The rollover resistance of the wall-climbing robot is an important parameter, which determines whether the robot can absorb on the glass surface safely and steadily. The cleaning course of the robot is from top to bottom of the surface. The force used when the robot is walking at a constant speed is shown in Figure 3.1.

The figure shows only the force seen from one side, but the other side is the same. Set F as the pulling force of the safety rope to which the robot is attached. This safety precaution is provided to prevent the robot from falling off in an emergency. At this time, its force analysis is not considered. The wipers on the upper and lower ends are pressed against the glass surface and are subjected to the reaction force Ff', Ff" of the glass surface. The robot's electric fan generates a negative pressure, so that the robot is pressed against the glass by atmospheric pressure. FP1', FP1" and FP2', FP2" are the pressures which are exerted by the negative pressure generated by the two fans, respectively. The positive pressure of the glass surface on the robot wheels is denoted as N1 and N2, respectively f1 and f2 are the rolling friction forces that the wheel receives when the robot is adsorbed on the glass surface. G is the gravity of the robot, acting at its center of gravity. Na is the resultant force of the equivalent supporting force acting on the seal ring. Fa is the sliding frictional resistance. In the figure, L0 is the distance between FP1 and FP2, L1 and L2 are the distances from the fulcrum of the wheel to the atmospheric pressure, Lf is the distance from the robot chassis to the cleaning position, L3 is the distance from the suction cup to the edge of the fuselage, the height of the robot's center of gravity relative to the glass surface is denoted as h.

Take the left end z of the following wheel as the fulcrum, and the robot's overturning moment is:

$$
\begin{aligned}
M_z = {} & FP_1'(2_{L_1} + L_o + L_2) + FP_1"(L_o + L_2) + F_f"(L_f \\
& + L_2 + L_3) + FP_2' * L_2 \\
& - F_f'(L_f + L_3 +^2 L_0 + L_1 + L_2) - N_1(L_1 + L_0 + L_2) \\
& - N_a(\frac{1}{2}L_0 + L_2) \\
& - G * h - FP_2" * L_2
\end{aligned}
$$

Mz is the sum of the torque received by the robot when z is the fulcrum. If Mz $\geq$ 0, the robot can safely adsorb on the glass, and the larger the Mz value, the better the is robot's adsorption performance. At the same time, as can be seen from the formula, lowering the robot's center of gravity can significantly increase the magnitude of the anti-overturning moment, and reduce the distance between the front and rear wheels of the robot. The value of Mz can also be increased, thereby increasing the safety of robot adsorption. Therefore, improving the adsorption performance of the robot can begin with the following:

(2) Analysis of Wind Forces on Robots During Working at Height

When the cleaning robot is working at a high altitude, it is affected by the air flow, and the sucker will be affected by the wind, and this must be considered. Therefore, it is necessary to analyze the wind force affecting the robot when it is working at a high altitude. The size of the wind force affecting the cleaning robot at different heights can be calculated with:

Wind speed estimation by wind class:

$$u = 3.02^* \sqrt{F^3} \tag{3.1.1}$$

where: u indicates the wind speed in km/h. F indicates the wind level (according to the Purcell wind rating table).

From the height h1, the wind speed at any height h2 can be deducted:

$$u_2 = u_1 \left(\frac{h_2}{h_1}\right)^{0.2} \tag{3.1.2}$$

where: U1 is the wind speed at height h1, in km/h.

U2 is the wind speed at height h2, in km/h.

Calculate wind pressure from wind speed:

$$P = v^2/16 \tag{3.1.3}$$

where: P is the wind pressure in kg/m2. v is the highest expected wind speed near the robot in m/s.

Finally, the formula for the wind force received by the sucker is derived as:

$$f = PAG \approx 0.044AGF^3 \left(\frac{h_2}{h_1}\right)^{0.4} \tag{3.1.4}$$

Now assume that the maximum wind level at 20m in the working environment of the robot is 8 (Pueb's wind level table), and the windward area of the robot is 0.2m2. With the above formula, the wind force of the robot sucker at 50m can be calculated as approximately 63.7N, the wind at 100m is about 84.1N, the wind at 150m is about 98.9N.

3.2 Analysis of Anti-Sliding Mechanics When Moves

The wall-climbing robot has a total of eight suction cups, as shown in Figure 2.1. In order to prevent the robot from sliding

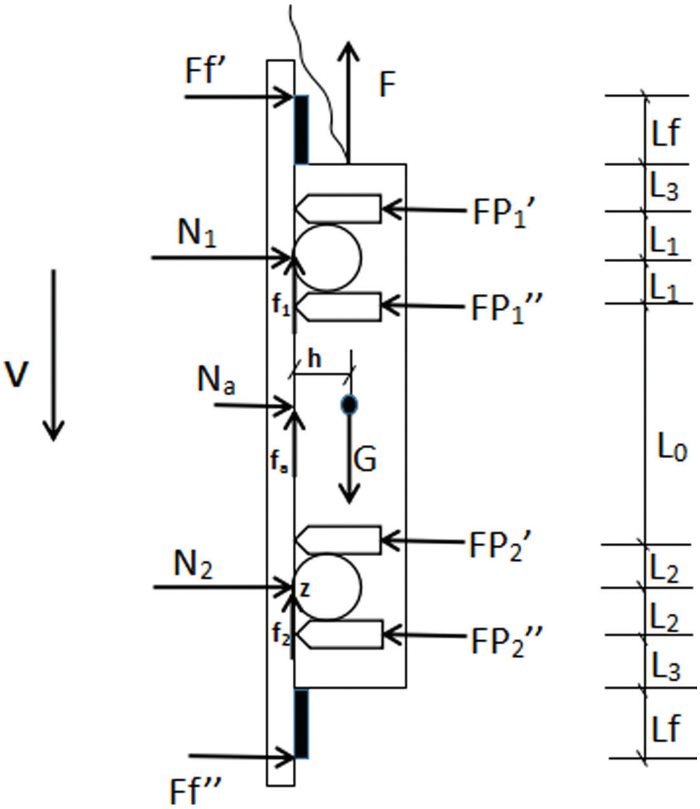

Figure 3 Robot wall climbing force analysis chart.

down the glass wall, and ensure that it can be stably adsorbed on the wall:

$$\sum_{i=1}^{4} f_i + f_a > G^* t \quad (3.2.1)$$

where: fi is the rolling friction force of each wheel when the robot moves, in N, fa is the resultant force of the sliding frictional resistance of each chuck, in N, G is the gravity of the robot and the load, acting at the center of gravity in N, t is the safety factor, its value takes 2.5∼3.

The normal support force of the curtain wall on the suction cup Na and the vacuum suction force ΣFP on the suction cup are equal to one pair of forces, and the directions of equal magnitude are opposite; that is:

$$N_a = \sum_{i=1}^{8} FP_i \quad (3.2.2)$$

Each wheel is subject to rolling friction:

$$f_i = N_i^* \mu \quad (3.2.3)$$

From equation (3.2.2), the resultant force of the sliding friction received by the chuck is:

$$f_a = N_a^* \mu = \mu^* \sum_{i=1}^{8} FP_i \quad (3.2.4)$$

where:μ is the friction coefficient, take $\mu = 0.4$;

The vacuum suction force of each suction cup is generated by the suction cup's effective area and vacuum. The expression is as follows:

$$FP_i = \Delta P_i^* A_i = \Delta P_i^* \frac{\Pi^* D_i^2}{4} \quad (3.2.5)$$

where: Δ Pi represents the degree of vacuum in KPa. Ai is the effective area of the sucker, the unit is cm^2. Di is the effective diameter of the suction cup, in cm. Substituting equation (3.2.5) into equation (3.2.4) can receive:

$$f_a = \mu^* \sum_{i=1}^{8} \Delta P_i^* \frac{\Pi^* D_i^2}{4} \quad (3.2.6)$$

Substituting equations (3.2.3) and (3.2.6) into equation (3.2.1) can be obtained:

$$\mu^* \left(\sum_{i=1}^{4} N_i + \sum_{i=1}^{g} \Delta P_i^* \frac{\Pi^* D_i^2}{4} \right) > G^* t \quad (3.2.7)$$

Since the diameters of the selected suction cups are the same, and the vacuum degree of each suction cup is assumed to be uniform, equation (3.2.7) can be used to obtain the relationship between the effective diameter D, vacuum degree Δ P, and gravity G of the suction cup when the robot can safely absorb without sliding down:

$$\mu^* \left(N + \Delta P^* \frac{\Pi^* D^2}{4^* t} \right) > G \quad (3.2.8)$$

According to the above analysis, the best adsorption force can be determined.

The mechanical modeling analysis above shows that the structural design of the cleaning robot can be well guided. By reducing the center of gravity of the robot and the distance between the front and rear wheels of the robot, etc., the magnitude of the anti-overturning moment is increased, and the value of Mz is increased to improve the robot's adsorption, thereby increasing the robot's adsorption safety. The relationship between the effective diameter D, the vacuum degree ΔP and the gravity G of the suction cup without slipping was obtained through wind resistance and anti-sliding analysis, and the best adsorption force was determined. In order to ensure the safe and reliable adsorption force and the flexibility of wall movement, the above analysis can improve the sport performance of wall-climbing robots, providing a good theoretical basis for design optimization and motion control of cleaning robots.

4. CONCLUSION

According to the research background of multi-suction sliding glass robots, we developed the design concept of the robot and used simulation software to simulate the establishment of a three-dimensional robot model, and carried out a simulation analysis of the movement and a detailed force analysis. We determined the relationshipbetween the effective diameter D, the vacuum degree ΔP, and the gravity G of the suction cup without slipping, and the best adsorption force. In the laboratory, based on the robot's three-dimensional model and the above mechanical modeling analysis, the optimization design of the robot was carried out. After completion of the production, the multi-suction sliding cleaning robot was tested. The experimental results showed that the curtain wall cleaning robot is stable on the surface, and the adsorption force is sufficient for the robot to walk freely on the glass.

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