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ORIGINAL ARTICLE

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Design and realization of a non-actuated glass-curtain wall-cleaning robot prototype with dual suction cups

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Abstract This paper describes a non-actuated glass-curtain wall-cleaning robot prototype that has been designed and realized based on some wall-climbing robots developed recently and common traits of glass-curtain walls of high-rise buildings. The robot hasn't its own driving mechanism, but it can move on smooth glass surfaces depending on its own gravity and the lifting force of the trolley crane on the roof while adhering to the surfaces using dual vacuum suction cups. Obstacles, such as horizontal window frames, can be crossed while cleaning. The safety analysis ensures that the robot can work reliably. The analysis on characteristics of suction cups using fluidic network theory is to enhance the adhering capacity of the robot. The control system utilizes two-level computer control strategy to achieve the robot's moving, cleaning and crossing obstacles. Experiments proved the robotic system is feasible and practical.

Keywords Crossing obstacles · Dual suction cups · Fluidic network theory · Glass-curtain wall-cleaning robot · Non-actuated · Safety analysis

1 Introduction

Due to the ability to relieve human beings from some hazardous works, there has been increasing great interest in developing various wall-climbing robots for construction, shipbuilding, chemical, petroleum and nuclear industries in the last decades. Wall-climbing robots can finish tasks ranging from cleaning glass-curtain walls, spray painting, fire rescue, sand blasting of gas tanks, inspecting and maintaining nuclear facilities and high pipes, remote supervisory to welding large, homogenous surfaces such as ships, dams, storage tanks and cooling towers in extremely hazardous environments which is often companied with radiation, high temperature, high pressure, high altitude and so on. All these tasks have an immediate need of automation. Wall-climbing robots, with special characteristics and abilities of adhering to wall surfaces, moving around, and carrying appropriate tools and sensors to work, are the best candidates. They would not only replace human workers to carry out specific dangerous tasks in hostile environments, but also reducing expenditures such as eliminating costly erection of scaffolding and staff costs.

A variety of wall-climbing robots aiming at specific tasks have been developed for wall surface maintenance applications in the last decades [1–24]. The moving mechanism of these robots can be roughly divided into five major categories: walking (legged) mechanism, wheeled mechanism, crawling mechanism, translation mechanism and track mechanism. Legged mechanisms ranging from two [1, 10], four [3, 5], six [7] to eight [2, 9] legs are employed in the design of slope- and wall-climbing machines. The main advantage is that the robot can move on rough surfaces and cross obstacles. The stability of the machine improves along with the increasing number of legs at the cost of increasing complexity. The control system is very complicated because of using complex harmonic gait control strategies. Meanwhile, the moving speed is low due to its discontinuous movement. To decrease the complexity, the wheeled mechanism is also a valid approach for wall-climbing applications [11, 15, 18]. This kind of mechanism has many advantages such as rapid movement and simple control. However, the climbing action still needs the support of gravity-defying mechanisms such as vacuum suction cups combined with a lifting mechanism. Moreover, the relative movement between suction cups and wall surfaces demands high performances

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for the sealing mechanism of suction cups. Simultaneously, the robot cannot adapt to rough surfaces or cross obstacles. Robots with crawling mechanisms can move continuously on surfaces and the speed can be subsequently improved greatly [1, 13, 15]. However, this kind of robot cannot also handle cracks or obstacles, and the payload capacity is small. Moreover, it is difficult to control the posture when the robot is moving. A climbing robot, named Cleanbot-I, which was developed for cleaning the glass wall of high-rise buildings, employed a translation mechanism [19]. The basic mechanism is a frame with a sliding section. Suction cups on the frame and sliding feet enable the robot to move forwards and rotate. The control strategy and working process are not complicated due to the easy movement mode of sticking-moving-sticking. Its disadvantage lies in the large size that hinders it from being used in narrow spaces. The movement of Cleanbot-I is also discontinuous with low speed and the complexity of the mechanism cannot afford reliable work. Moreover, a kind of climbing robot Cleanbot-II with a track mechanism has also been developed for cleaning glass surfaces [20]. Using a chain-track and 52 suction cups for adhesion, Cleanbot II can achieve continuous movement, cross an obstacle with a height less than 6 mm and track a circular path with flexible structures. This kind of mechanism is so complex that its work cannot be reliability guaranteed.

The adhesion methods adopted by wall-climbing robots can be divided into three categories: magnetic adhesion, thrust force and vacuum suction cup. The magnetic adhesion, including permanent magnetization and electrical magnetization, is only suitable for ferromagnetic surfaces [7, 13–15]. In thrust force mode, airscrew is usually used to produce thrust force and press the robot on the wall surface [1], the mechanism can help robots avoid obstacles while moving, but its unsatisfied stability hinders this method from being used in practice extensively. The vacuum suction cup, as the most commonly adhesion method, can be widely adopted to less rough surfaces because it brings strong absorption to the surface in spite of what kind of material, such as glass, ceramics tile and cement [1–6, 9–12, 15–21].

Many prototypes of climbing robots have been developed using different motion systems and adhesion methods in many research centers, just to name a few. However, aiming at cleaning glass-curtain walls of high-rise buildings, the robot must have some specific traits differing from other kinds of robots. So, the locomotion method and the validity of the robot are the main considerations. In recent years, including Cleanbot-I and Cleanbot-II, some glass-curtain wall-cleaning robots have been developed [15–24]. Fraunhofer IPA in Germany developed a variety of glass facade cleaning robots aiming to different building types, such as SIRIUSc and the balloon-based robotic system [22–24]. Furthermore, a wall-cleaning robot using the wheeled mechanism with a single large suction cup is developed [18]. A lightweight small robot for window cleaning is also proposed [21]. In some cases, the design of wall-climbing robots requires the machines to move and operate on the wall surface swiftly while defying the action of gravity. Moreover, the robot's adaptability to different wall surfaces is important. These demands will lead to the complexity of the mechanism and control system, and high cost. However, for glass-curtain walls, due to the constructional complexity, it seems impossible to develop a robot that can adapt to all kind of building structures accompanied with high working efficiency and low cost. We notice that the flat glass-curtain wall with horizontal or vertical window frames is common in reality and develop a non-actuated glass-curtain wall-cleaning robot prototype with dual suction cups in this paper. The beauty of the robot is the simplicity of its moving mechanism. Furthermore, when adhering to glass surfaces, the robot can move on the surface and cross obstacles while cleaning. Experiments proved that the robotic system is feasible and practical. The robot may adapt to other applications when using various tools instead of the cleaning system.

This paper is organized as follows: In Sect. 2, the mechanism of the non-actuated wall-cleaning robot with dual suction cups including the cleaning system is firstly developed. The process of crossing a horizontal window frame while cleaning are then presented and analyzed. The safety analysis is introduced in Sect. 3. Section 4 gives the analysis on the characteristics of suction cups when the robot meets concave joints on surfaces. In Sect. 5, the control system frame is proposed. In Sect. 6, experiments are given to verify the function of the robot prototype. The conclusion and future work are presented in Sect. 7.

2 Mechanism development of the robot

The following components are absolutely necessary to glass-curtain wall-cleaning robots and are independent of building shapes and surface types:

– Mechanism for moving, adhesion and crossing obstacles on glass surfaces,
– Control system, sensors, navigation and operator interface,
– Equipments for preventing the robot from falling,
– Energy and cleaning materials supply and,
– Cleaning system.

2.1 Robotic system concept

The robotic system is composed of three main subsystems: the body of the robot, the trolley crane and the portable monitoring case (see Fig. 1).

The body of the robot, linked to the crane with a steel cable, is mainly composed of the adhering mechanism with dual suction cups, the sealing mechanism, obstacle-detecting sensors and the cleaning system. The structure diagram is shown in Fig. 2. The adhering mechanism can ensure that the robot adheres to glass surfaces and crosses obstacles while cleaning. It consists of two large rectangle suction cups, an “H” type negative pressure occurring chamber, two vacuum pumps, two sliding blocks in each

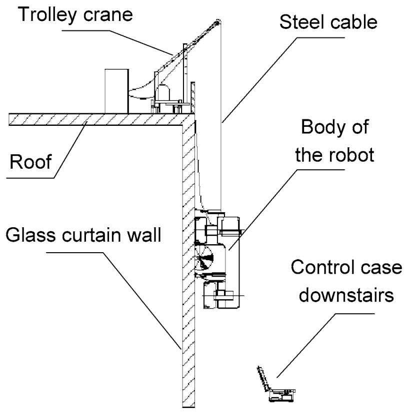


Fig. 1 The wall-cleaning robotic system

suction cup, air cylinders, pneumatic accessories, and four sliding barrels connecting suction cups and the occurring chamber. After two vacuum pumps are turned on and one or two suction cups smoothly clings to the glass surface, the negative pressure will be gradually developed in the closed occurring chamber. Meanwhile, suction cups can adhere to the glass surface tightly with the help of the sealing mechanism. When the trolley crane is controlled to unwind the steel cable downwards, the robot can slide along the glass surface with the help of its own gravity force. The sealing mechanism plays a crucial role in suction cups of some wall climbing robots [15]. Due to the special mechanism of our robot, the demand to the sealing mechanism is decreased. So, air leakage on suction cups would happen but it is allowable to some extent. The sealing mechanism includes four size-adjustable follow-up rollers near four corners of each suction cup and double-layer rubber rings around each suction cup. The follow-up rollers are used to prevent the rubble rings from contacting too tightly with the wall surface. It is useful to decrease the friction coefficient and reduce wear of rubber rings when the robot slides down while adhering to flat glass surface. In order to maintain the horizontal posture of the robot, the sealing mechanism must be adjusted very smoothly along the horizontal direction of suction cups. The double-skin rubber rings are chucked by thread groove on aluminuim plates along the edge of each suction cup in order to avoid excessive deforming. Four groups of photoelectric sensors are used to detect obstacles, such as horizontal window frames. The lower suction cup, the recycle-water board, the upper suction cup and the surface-scrape board withdraw sequentially when individual two bilateral symmetry sensors detect obstacles, and project sequentially after crossing obstacles individually.

The cleaning system plays an important role for glass-curtain wall-cleaning robots and should show good working performance. Our robot uses a very sophisticated cleaning tool, which has special features during cleaning glass surfaces automatically. The whole cleaning procedure is mainly composed of water-spray, washing agent supply, brush-scrub, wastewater-recovery, sewerage-filtration and final surface-scrape. The cleaning system is mainly composed of a flexible brush (1500 mm long), a rotary axis, a brush encasing, four water pumps, a water tank, a recovery-water board, a filter, eight ejection nozzles, a DC servomotor, a liquid level sensor and so on. The specially designed flexible brush is twisted and fixed on the horizontal long rotary axis drove by the DC servomotor with sync belt actuating mechanism. The brush rotates with high speed, whips and cleans the glass surface like innumerable short twines after the surface is coated with

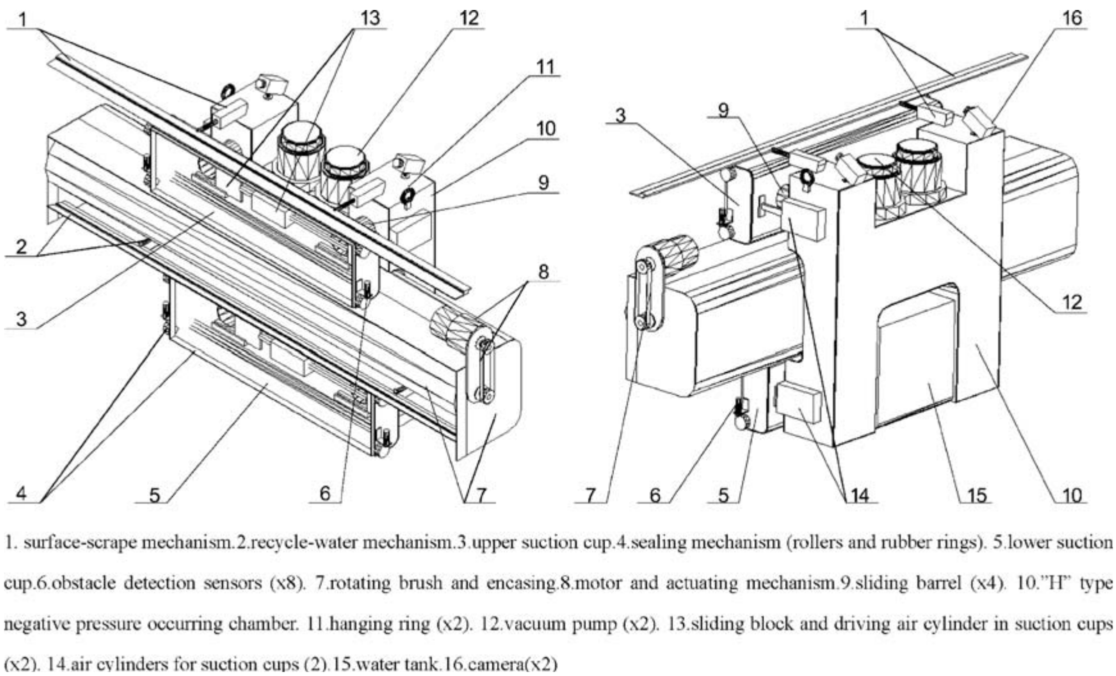


Fig. 2 The structure diagram of the robot

sprayed cleaning liquid. The washing agent supply, the working intensity and the cleaning time/velocity of the rotating brush should adapt to the degree and property of dirty on different glass surfaces in order to attain high cleaning efficiency. As water is not allowed to flow down along the glass surface, the recovery-water mechanism reclaims and filters the wastewater into the water tank for reusing, which increases the utilization rate of water and helps to clean more areas. The surface-scrape board is used to scrape glass surfaces that have been cleaned just now and erase the residual water. Due to difficulties in water supply for cleaning a tall building, water is located in a water tank. A supporting vehicle on the ground is also necessary to supply the cleaning liquid through a hose. In all, the cleaning system can clean glass surfaces efficiently and environmentally friendly.

The trolley crane as the security system on the roof of high-rise buildings is widely used in many applications [19, 22, 23]. This system is often utilized as auxiliary equipment to prevent the robot from falling and doesn't interfere with the robot's actions. In our research, the trolley crane must synchronize all mechanisms of the robot to finish the whole working procedure due to the non-actuated feature. At the meantime, once the robot cannot adhere to the wall surface reliably, the crane can prevent the robot from falling. The crane system consists of a trolley, a fixed rail, a support frame, two hanging rings on the robot, a steel cable, a rotary encoder and a revolution axis of the support frame. Moreover, power and air supply are afforded on the roof. Due to its significance, the crane has been given a special design, such as anti-swing of the steel cable, localization of the robot and fail-safe analysis when encountering strong wind.

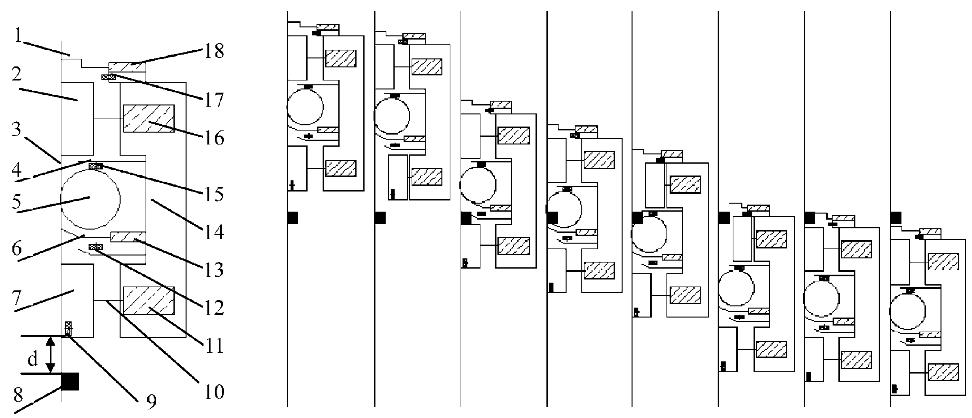
The portable monitoring case is placed downstairs and offers a convenient control approach during the whole operation process. There is not any physical connection between the control case and other robotic parts. All instructions are sent to the robot and the crane using wireless control strategy. Furthermore, the active states of the robot and the crane are accepted and displayed on a LCD that is placed on the operating panel of the control case. A wireless video system is used to monitor just being-cleaned glass surfaces to offer reference control scheme.

2.2 Crossing the horizontal window frame while cleaning

The horizontal window frames, namely obstacles, separate the whole glass-curtain wall surfaces into many sections. After completing current cleaning work in one section, the robot must cross the horizontal window frame to enter another section. The local information about obstacles is not available but the robot would encounter them in its cleaning path. So, the robot detects obstacles ceaselessly using photoelectric sensors when sliding down. After obstacles are detected, the control system generates corresponding steps to make the robot cross them successfully and at least one suction cup is guaranteed to adhere to glass surfaces at all times. Photoelectric sensors, which are distributed symmetrically aside on the body of the robot, detect whether the window frame has approached to the lower suction cup, the recycle-water board, the upper suction cup and the surface-scrape board or not in turn. These sensors are divided into four groups and each group has two. Supposing that the horizontal window frame protrudes the glass surface less than 2−3 in, the process of crossing horizontal window frames is illustrated in Fig. 3 using a similar sticking-releasing-sticking method of suction cups.

There are two major steps to cross the window frame: the first step is to measure the distance, denoted by d in Fig. 3, between the lower boundary of the lower suction cup and the horizontal window frame by employing the first group of sensors. The distance d is an important factor for estimating the current position of the robot in each window section and determining the action occasion of four components of the robot to cross obstacles. The second

Fig. 3 The robot crossing a horizontal window frame



1.surface-scrape board 2.upper suction cup 3.glass-curtain wall 4.brush encasing 5.rotating brush 6.recycle-water board 7.lower suction cup 8.horizontal Window frame 9.photoelectric sensor I 10.sliding barrel 11.air cylinder I 12.photoelectric sensor II 13.air cylinder II 14.negative pressure chamber 15.photoelectric sensor III 16.air cylinder III 17.photoelectric sensor IV 18.air cylinder IV step is to cross the horizontal window frame in sequence. When d gets to a desired value that is determined by the sliding velocity of the robot along the glass surface, the robot will prepare to take action. Four components withdraw by individual air cylinders in sequence, when d becomes larger again or the other three groups of sensors cannot detect the projected frame, individual air cylinders sequentially push four components to adhere to the glass surface again. Because the distance measurement and switch-status of sensors are different during the period of crossing obstacles, the robot knows it has crossed the window frame and continues to clean the current window section.

Note that the rotating brush can clean window frames due to its flexibleness and needn't withdraw when the robot is crossing obstacles. Moreover, because the robot only slides down along the glass surface, vertical window frames cannot be crossed. Most importantly, supposing the robot cannot maintain its horizontal posture when sliding down, two sensors of lower suction cup may measure different values, then the robot cannot correctly determine its action occasion and fail in crossing the window frame. So the sealing mechanism and the robot's posture adjusting strategy should be taken into account although the robot can slide down without obvious deflection during working at present. In fact, the horizontal window frame that the robot can cross is restricted to the robotic mechanism dimension in practice.

3 Safety analysis

As a kind of special robot, the security and reliability of wall-climbing robots can be greatly influenced by its own gravity force that may make the robot fall from the glass surface and be damaged. Therefore, in many cases, the gravity force of wall-climbing robots is not welcome and the crane on the roof is usually adopted in case of emergency. In our research, we utilize the gravity force as the driving force and help the robot to slide down along glass-curtain wall surfaces while the steel cable is being unwound. This method has mainly three prominent traits: simplified mechanism, increase in the ratio of payload/gravity and confirmed safety of the robot.

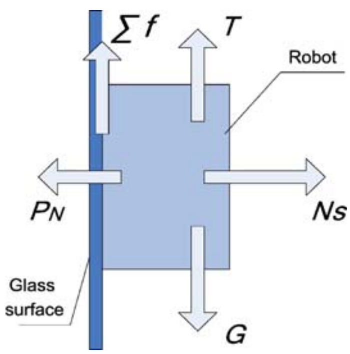


Fig. 4 Mechanical analysis of the robot

The robot can move on glass surfaces accompanied by the coordination of the gravity force and the lifting force of the crane while adhering to the surfaces with one or two suction cups. According to Fig. 4, the driving force F is the difference of the gravity force G, the lifting force T and the total friction force $\sum f$. If F is greater than zero, the robot can slide along the glass surface. However, due to the complexity of different glass surfaces, it is very difficult for the crane to control the unwinding velocity of the steel cable.

Supposing that the gravity center is located at the vertical centerline of the robot in alignment with the suspension point of the cable, and the line parallels the glass surface, the robot may not incline or roll over in the horizontal direction and bump glass surfaces. Therefore, the robot can maintain the horizontal attitude and slides down against the glass surface due to its own gravity force when the steel cable is being travelled down on condition that some requirements are fulfiled. These requirements include steady negative pressure in suction cups, good adaptability to glass surfaces and so on. Thus, in order to work reliably and move downwards on surfaces with acceleration, deceleration or uniform speed, the following equations must be satisfied with:

(1) When the robot adheres to the vertical glass surface and the steel cable has not be unwound, we can attain:

$$\sum \vec{F} = 2\mu_1 \Delta p_1 A_c - G \leq 0, \quad \Delta p_1 \leq G/(2\mu_1 A_c) \tag{1}$$

where μ_1 is the equivalent static fiction coefficient between two suction cups and the glass surface; Δp_1 is the negative pressure in suction cups when the robot adheres to the surface with two suction cups; A_c is the effective sealing area of suction cups.

(2) In order to ensure that the robot can move on glass surfaces while adhering to the surfaces, after the crane unwinds the steel cable, the following conditions should be satisfied:

$$\sum \vec{F} = 2\mu_2 \Delta p_2 A_c - G + T \leq 0 \quad \Delta p_2 \leq (G - T)/(2\mu_2 A_C). \tag{2}$$

Therefore, we can obtain $\Delta P_c = \min|\Delta p_1, \Delta p_2| > 0$. Where μ_2 is the equivalent coefficient of kinetic fiction between suction cups and glass surfaces; Δp_2 and ΔP_c are the negative pressure in suction cups when the robot begins to slide downwards; T is the lifting force of the crane and conforms to the inequality: $0 < T = G - P_N \cdot \mu$.

(3) When the robot moves downwards with two suction cups and the brush whips the surface for cleaning, we can write:

$$\begin{aligned} &\sum \vec{F} = \mu_2(2\Delta p_3 A_c - N_S) - G + T \le 0 \\ &N_S > 0 \\ &2\Delta p_3 A_c - N_S \ge 0 \\ &N_S/(2A_c) \le \Delta p_3 \le [(G-T)/\mu_2 + N_S]/(2A_C) \end{aligned} \tag{3}$$

where Δp_3 is the negative pressure in suction cups when the robot is cleaning the surface; N_S is the reaction force acting on the robot from the surface when the rotating brush rotates.

(4) Similarly, when the robot moves downwards with a single suction cup adhering to the glass surface, we only substitute A_c for $2A_c$ in Eq. 3. Note that the robot can't roll over at that time because the surface-scratch board and the recycle-water board are leaning against the surface tightly.

According to equations listed above, we can generalize the following inequality:

$$N_S \le P_N = 2\Delta p_c A_c (\text{or} \Delta P_c A_c) \le \frac{G}{\mu},\ P_N = \sum f/\mu \tag{4}$$

where P_N is the "adhering force" acting on glass surfaces when the robot adheres to the surface with one or two suction cups; P_c is the negative pressure in suction cups; μ is the total equivalent friction coefficient between one or two suction cups, the rotating brush, the surface-scratch board, the recycle-water board of the robot and the glass surface.

In order to maintain horizontal posture of the robot and avoid inclination, $\sum f$ should be as small as possible than the gravity force, but the value of N_S must be always maintained.

It's well known that μ may vary with the degree of dirt on different glass surfaces of high-rise buildings. Also, there is inevitable down-running water seepage through the recycle-water board while cleaning. Moreover, the follow-up rollers of suction cups may slip. Therefore, these cases lead to a changeable value of μ. Similarly, P_N may be affected by unpredictable air leakage of suction cups when different-sized concave joints on glass surfaces are encountered, and potential inactivation of the sealing mechanism. Furthermore, when the robot is crossing obstacles or there is additional random force on the robot due to strong wind at high altitude, P_N may change. Meanwhile, the cleaning intensity and the cleaning time/velocity of the rotating brush should be accorded with the degree of dirt on different glass surfaces. Therefore the reaction force N_S caused by the acting force of the rotating brush varies, and then the adhering condition also changes. In all, three variables in Eq. 4 may vary in different cases. Our intention is to control the adhering force P_N and make the robot clean the glass surface with trouble-free working.

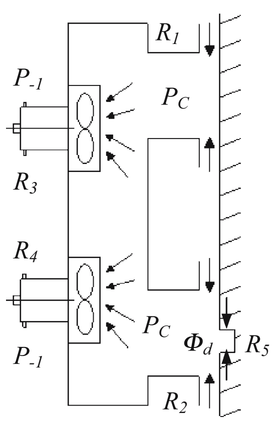


Fig. 5 The model of the suction cup

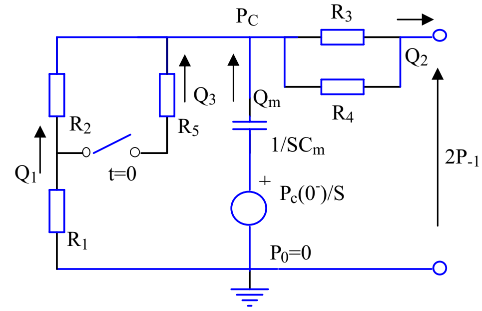


Fig. 6 The equivalent circuit model due to air leakage

4 Characteristics analysis of suction cups

We have developed an approach using fluidic network theory to study and analyze dynamic characteristics of vacuum suction cups in order to enhance the capability of adhering of wall-climbing robots [18]. Here, we will also use the approach to present roughly analytical results on characteristic of negative pressure in suction cups when the suction cups meet air leakage due to concave joints on glass surfaces. Based on fluidic network theory, the model of the suction cup and the equivalent circuit model are presented in Figs. 5 and 6, respectively. The flow passage between the sealing mechanism and the glass surface is regarded as a rectangular pipeline and the flow resistance is R_1 and R_2. The flow resistance of two vacuum pumps and the concave joints (Φ_d) are R_3, R_4 and R_5, respectively.

Assuming that P_c keeps steady before the robot meets concave joints with Φ_d equivalent diameter. When $t=0^-$, the initial parameters are:

$$\begin{aligned} P_c(0^-) &= \frac{R_1+R_2}{R_1+R_2+R_{34}} 2P_{-1},\ Q_1(0^-) \\ &= \frac{2P_{-1}}{R_1+R_2+R_{34}} \\ &= Q_2(0^-),\ Q_m(0^-) \\ &= 0 \end{aligned}$$

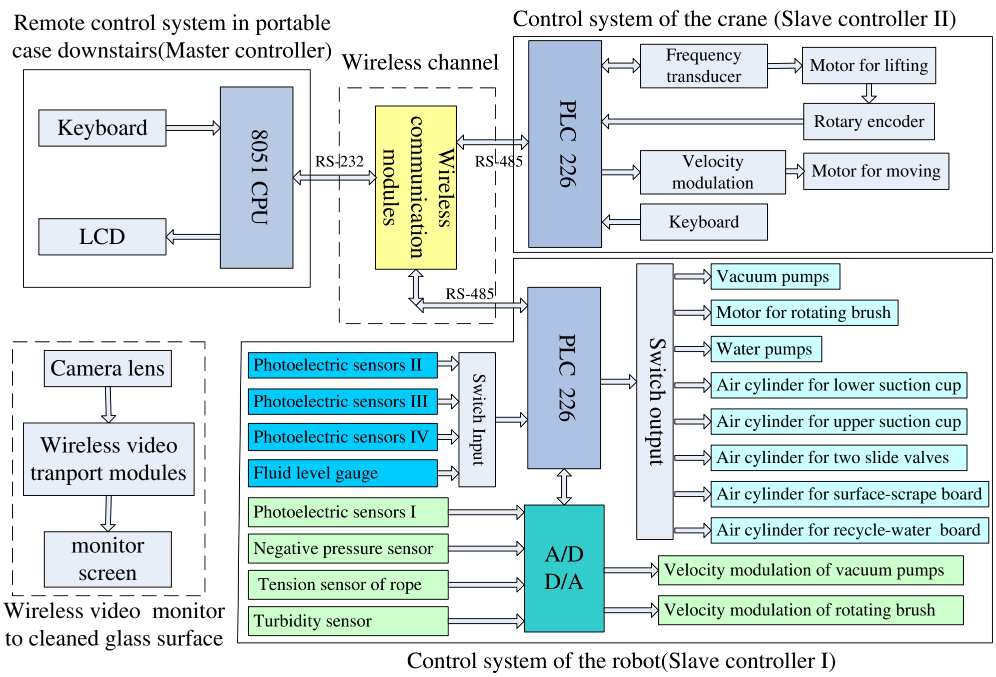


Fig. 7 Control system frame of the wall-cleaning robot

where Q is fluidic mass flux, $R_{34}=R_3R_4/(R_3+R_4)$, P_{-1} is the max vacuum of the pump, P_c is the vacuum pressure in the suction cup and P_0 is the standard air pressure. When t≥0, we can have:

$$Q_2(s) = \frac{2P_{-1}/s - P_c(s)}{R_{34}} = \left(P_c(s) - P_c(0^-)/s\right)\cdot sC_m + Q_1(0^-) + P_c(s)\big/(R_{25}+R_1).$$

After rearrangement,

$$P_c(s) = \frac{\frac{R_1+R_2}{R_1+R_2+R_{34}}2P_{-1}}{s+\frac{1}{R'C_m}} + \frac{2R'P_{-1}}{R_{34}}\left(\frac{1}{s} - \frac{1}{s+\frac{1}{R'C_m}}\right).$$

By Laplace inverse transformation, we can obtain:

$$P_c(t) = \frac{2(R_{25}+R_1)P_{-1}}{R_{34}+R_{25}+R_1} + 2\left(\frac{R_1+R_2}{R_1+R_2+R_{34}} - \frac{R_{25}+R_1}{R_{34}+R_{25}+R_1}\right) e^{-t/\tau}P_{-1} \tag{5}$$

where $R_{25}=R_2R_5/(R_2+R_5)$,$R'=R_{34}(R_{25}+R_1)/(R_{34}+R_{25}+R_1)$,$C_m$ denotes the flow-capacitance and τ is the time coefficient of the dynamic response curve and equals to $R'C_m$.

According to Eq. 5, we can get:

(1) The instantaneous value of P_c remains constant when the robot meets concave joints, but τ is expected to be as long as possible for increasing the response time and avoiding falling.
(2) C_m and R has great effects on P_c and they are determined by the structure of the suction cups.

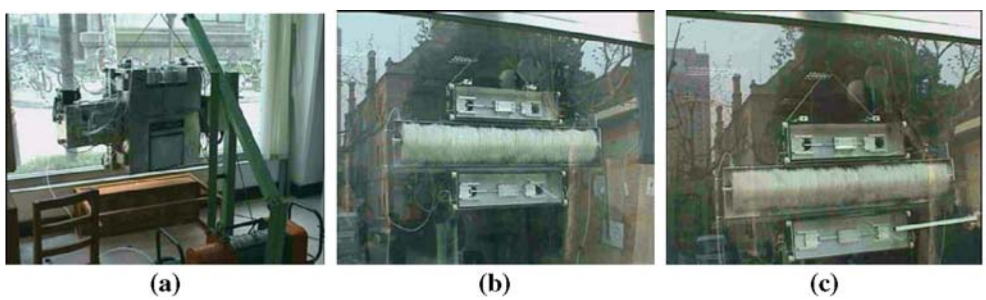


Fig. 8 Pictures of the robot in laboratory

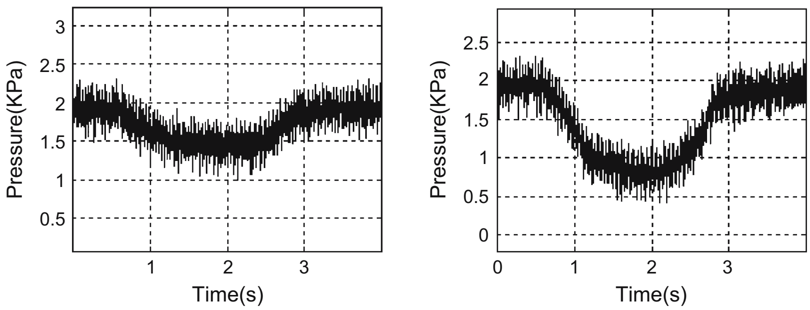


Fig. 9 The response curves of P_c encountering different-sized concave joints (Φ_d)

(3) When $t=\infty$, $P_c(\infty)=2P_{-1}(R_{25}+R_1)/(R_{34}+R_1+R_{25})<P_c(0)$, P_c will decrease to a stable value. If P_c reaches a certain value, defined as $P_d=K_cP_{-1}$, the robot may fall. Therefore, the basic condition of robot adhering to the glass surface reliably is $P_c(\infty)/P_{-1}\geq K_c$, namely $2(R_{25}+R_1)/(R_{34}+R_{25}+R_1)\geq K_c$. And then, the allowable max value of Φ_d is determined in practice. Where K_c denotes an assurance coefficient (non-dimensional quantity) to ensure that the robot can adhere to the wall surface reliably.

In conclusion, some principles of design on suction cups are obtained in order to increase the capability of adhering and the adaptability to different wall surfaces of wall-climbing robots.

5 Control system

The control system has been attached more importance because wall-climbing robots always work in hazardous circumstances and must work reliably. The whole control system is based on a master and two slave controllers using wireless communication method and the schematic diagram is presented in Fig. 7.

The master controller is located in a portable monitoring case downstairs and can be manipulated portably by a human operator. It plays the following roles: planning the moving track manually, getting working information to adjust the active status or stopping all actions of the robotic system in case of emergency, and communicating with two slave controllers by wireless channel. Furthermore, as a human interface, the controller gives the active status of the whole robotic system. Two slave controllers, using programmable logic controllers (PLC), are embedded in the robot and the crane, individually. They mainly synchronize the moving mechanism, adhering mechanism and the cleaning system of the robot with the crane using feedback signals of multi-sensors, and transfer state information to the master controller, individually. The wireless video system is also used to monitor the degree of cleanliness on glass surfaces just being cleaned and to offer reference control information to further effective work. The higher the robot climbs, the longer the wire or steel cable is. So the wireless communication method is adopted to reduce the complexity of communication.

Due to its high stability and modularity, PLCs are chosen to control the whole motion of the robot and the crane. The local control system of the robot are mainly divided into three modules as follows and each module comprises several subsystems: the first module controls the adhering mechanism which is responsible for moving on glass surfaces while adhering to the surfaces with one or two suction cups, and detects and crosses obstacles; the next module finishes surface cleaning action of the cleaning system harmoniously; the last module is devoted to communicate with the master or the other slave controller. Pneumatic cylinders push or withdraw two suction cups, the recycle-water board and the surface-scrape board, and open or close sliding valves between suction cups and the "H" type negative pressure occurring chamber. A negative pressure sensor is used to measure the degree of the negative pressure developed by two vacuum pumps. A closed loop fuzzy control algorithm is adopted to regulate the negative pressure for reliable movement and good adaptability to different glass surfaces. In order to finish the whole cleaning procedure, the DC motor drives the rotating brush with different working velocities. Water pumps are used to supply and reclaim water and a fluid level gauge measures the water level of the water tank. Furthermore, for the coordination control of crossing obstacles, four groups of photoelectric sensors are adopted. The PLC as the local control system of the crane implements all actions on the roof including unwinding the steel cable, safeguarding and self-positioning of lateral movement along the external wall of the construction. Most importantly, the anti-swing of the steel cable and the localization of the robot should be considered here.

Table 1 Technical specifications of the robot

Dimensions	1500×800×400 mm	Efficiency of cleaning	≥200 sq.m. per hour
Mass	60 kg	Water consumption	≤0.025 kg per sq.m.
Cleaning width	1500 mm	Height of obstacle	≤2~3 in

6 Experiments

To verify the effective function of the robot prototype, experiments were performed and some pictures in laboratory are shown in Fig. 8. The adhering ability and the adaptability to glass surfaces of suction cups, the ability of movement sliding along glass surfaces, the effectiveness of the cleaning system and the reliability of the control system are tested. Among these, the adhering capacity is one of the most important things for reliable work. Figure 9 presents a set of negative pressure curves when the short-term air leakage happens on a suction cup due to encountering different-sized concave joints on surfaces (man-made holes on the robot in lab). The results can verify whether the robot has good adhering capacity and adaptability or not.

In conclusion, experiments indicate that the non-actuated wall-cleaning robot can basically accomplish the cleaning task of glass-curtain walls even if there are some occurring problems if the robot wants to be put into practice. In comparison with other kinds of wall-climbing robots with relative complex mechanism, the robot can be widely used to clean flat glass-curtain walls with horizontal window frames due to its simple mechanism, low cost and easy control.

The main technical specifications of the robot are listed in Table 1.

7 Conclusions and future work

This paper describes a non-actuated glass-curtain wall-cleaning robot prototype with dual suction cups. The robotic system is specifically designed for flat glass-curtain walls with horizontal window frames that are common in high-rise buildings and the whole system is introduced in detail. Compared with other wall-climbing robots, the beauty of the robot is its simple mechanism. The process of crossing a horizontal window frame while cleaning is presented. The safety analysis, the characteristics analysis of suction cups and the control system are also proposed in order to improve the service ability of the robot. Experiments demonstrate that the robot can be applied in practice. Further work may be concentrated on mechanical improvement and optimization, and the design on the robust control system in order to enhance the robot's adaptability to specific environments and to increase its intelligence action.

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