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Development and applications of wall-climbing robots with a single suction cup

Yanzheng Zhao*, Zhuang Fu*, Qixin Cao* and Yan Wang†

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SUMMARY

In this paper, wall-climbing robots with a single suction cup are studied. The robots mainly consist of three parts: A vacuum pump, a sealing mechanism and a driving mechanism. Basic conditions that the robots can adhere to and move reliably on a vertical surface are first established, then the sealing mechanism with an air spring and regulating springs is analyzed, and the synthetic rigidity formula for the sealing loop is obtained. Finally, two application examples are given: One for the ultrasonic inspection of cylindrical stainless steel nuclear storage tanks, and the other for cleaning high-rise buildings.

KEYWORDS: Wall-climbing robot; Single suction cup; Ultrasonic inspection; Cleaning of high-rise buildings

1. INTRODUCTION

Wall-climbing robots can be employed to carry out maintenance,[1] inspection[2] and rescue works in extremely hazardous environments affected by radiation, high temperature, high pressure, or on vertical walls. These conditions are not only dangerous but also difficult for human beings. It is important to carry out research on this kind of robots to fulfill their mission better for replacing people in such circumstances.

A wall-climbing robot must have two basic functions: adherence and moving. The adherence function is realized through vacuuming, magnetization, or thrust. A vacuum can be produced by vacuum pumps, centrifugal air pumps or the spray of compressed air. Vacuuming is widely used because it brings strong adherence to the surface regardless of the material the surface is made of. Magnetization can be either permanent magnetism[3] or an electro-magnetism.[4] It is only suitable for surfaces made of magnetic materials. In a thrust mode, an airscrew is usually used to produce a thrust and the robot is pressed onto the surface.[5,6]

There are three means (wheel, crawler and walking two feet or more), to realize the moving function. Different adherences and moving modes can be combined to form different kinds of a wall-climbing robot according to the specific application and needs.[7–10] In this paper, wall-climbing robots with a single suction cup are studied.

The paper is organized as follows: In Section 2, the major mechanism of the robot is introduced. The necessary conditions to which the robots can adhere and move reliably on the wall are analyzed. Specifically, the composite spring rigidity of the sealing loop is investigated. In Section 3, a robot with an omni-directional driving mechanism for ultrasonic inspection of cylindrical stainless steel nuclear storage tanks is introduced. A two-wheel robot with cleaning devices, used to clean high-rise buildings, is discussed in Section 4.

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* Research Institute of Robotics, School of Mechanical Engineering, Shanghai JiaoTong University, 1954 Huashan Road, Shanghai 200030 (P.R. of China).
† Robot Research Institute, Harbin Institute of Technology, 92 Dazhi Street, Harbin 150001 (P.R. of China).
Corresponding author: Zhuang Fu. E-mail: zhfu@sjtu.edu.cn

2. WALL-CLIMBING ROBOT WITH A SINGLE SUCTION CUP: THE SYSTEM

2.1. Basic structure of the system

The structure diagram of the wall-climbing robots used in the present study is shown in Fig. 1. There are three main parts: a vacuum pump, a sealing mechanism and a driving mechanism, each is discussed in more detail below.

1) Vacuum pump. Because of the relative movement and the gap between the sealing loop and the wall, the air leaks from the cup in the process of moving. A high-speed centrifugal air pump (voltage: 220 V; power: 1000 W; rotation speed: 23000 r/min; limit vacuum: 1800 mm H_2O) is employed to draw in the air leakage and to keep the dynamic balance of the negative pressure. The response curve of the negative pressure in the sucker is shown in Fig. 2.

2) Sealing mechanism. In order to have enough negative pressure in the sucker and make the robot adhere reliably to the wall, there must be a sealing method. An air chamber/regulating spring combination is adopted here for that purpose. The regulating spring provides the necessary sealing pressure and helps to improve the surface adaptability of the robot. Considering that the minimum design diameter of the working surface is about 6 meters, a layer of wearable composite material is added to the outside of the air chamber in order to keep the air spring effective and to reduce the friction between the sealing loop and the wall. Tests have proven that the sealing method employed is satisfactory.

3) Driving mechanism. Movement may be realized through a wheel or a crawler mode depending on the actual situation. Both omni-directional driving mechanisms and two wheel mechanisms are used in the application examples given later.

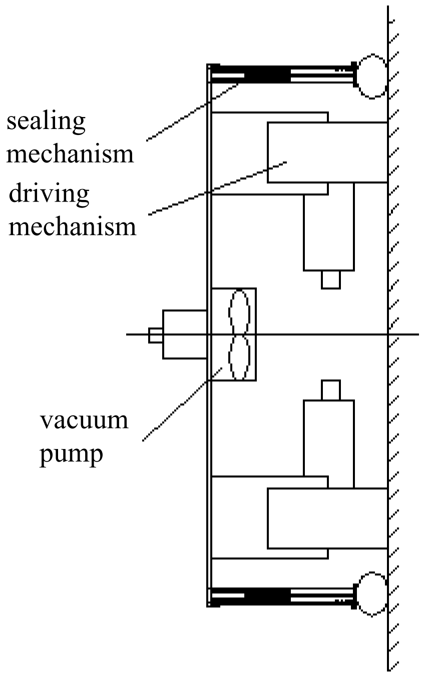

Fig. 1. The structure diagram of a wall-climbing robot.

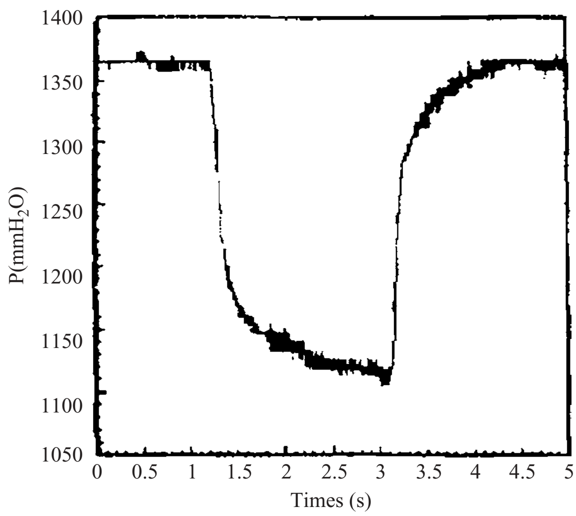

Fig. 2. The response curve of the negative pressure in the sucker.

2.2. The conditions for establishing reliable adherence to a vertical surface

In order to ensure that the robot can immovably adhere to vertical surfaces, the following conditions have to be satisfied:

$$\sum \vec{F} = \mu\xi\Delta p_1 A_c - G \geq 0, \qquad \Delta p_1 \geq G/(\mu\zeta A_c) \tag{1}$$

and

$$\sum M = \mu\zeta\Delta p_2 A_c l - Gh \geq 0, \qquad \Delta p_2 \geq Gh/(\mu\zeta A_c l) \tag{2}$$

where μ is the static friction coefficient between the driving wheels and the wall surface; ξ is the ratio of the pressure produced by the sucker to the pressure acting on the driving wheels, usually, $0.8 \leq \xi \leq 0.9$; ΔP_c, Δp_1, Δp_2 are the pressure differences inside and outside of the sucker (P_a); A_c is the effective suction area of the sucker (m^2); W is the weight of the robot (N); l is the distance between the point acted on by composition of the suction forces and pivot (m); h is the height of gravity center of the robot away from the wall surface (m).

Thus, in order to make the robot's adherence to the wall surface reliable, the negative pressure in the sucker has to satisfy the condition:

$$\Delta p_c = \max|\Delta p_1, \Delta p_2| \tag{3}$$

2.3. The conditions that the wall-climbing robot can move on vertical surfaces

When the robot moves on vertical walls, because of the gravity, there must be a strong negative pressure in the sucker. Thus, in order to make the robot accelerate upward, the following conditions have to be satisfied:

$$\sum \vec{F} = \sum T/r - G - F_s \geq ma, \qquad \sum T \geq (G + F_s + ma)r \tag{4}$$

and

$$\sum T/r \leq \mu\zeta\Delta p_3 A_c, \qquad \sum T \leq \mu\zeta\Delta p_3 A_c r \tag{5}$$

where: ΣT is the total driving moment of the wheels (Nm); r is the radius of the wheels (m); F_s is the total friction between the sealing loop and the wall(N); Δp_3 is the pressure difference inside and outside of the sucker (P_a);

Hence:

$$\Delta p_3 \geq (G + F_s + ma)/(\mu\zeta A_c) \tag{6}$$

Thus, in order to make the robot accelerate upward, the negative pressure in the sucker has to satisfy the following conditions:

$$\Delta p_c \geq \max|\Delta p_1, \Delta p_2, \Delta p_3| \tag{7}$$

2.4. The realization of the adherence function of the wall-climbing robot

Adherence is a basic and distinguishing function of wall-climbing robots. To make the robot adhere to the wall reliably, a sucker is indispensable. There can be a single sucker or several suckers. A multi-sucker often adopts a walking mode or a crawler mode. When robots with multi-sucker move on the wall, there is no relative movement between the sucker and the wall surface. A single sucker often adopts as wheels mode, and there is relative movement between the sucker and the wall surface. Because of its simple structure, high moving speed and convenient control, wall-climbing robots with a single suction cup have been widely used. This kind of robots is studied in this section. Because there is a relative movement between the sealing loop of the sucker and the wall, it is required that the sealing loop must be able to adapt to the concave and convex parts of the wall to some extent. Meanwhile, the sealing loop must tolerate some wear and tear

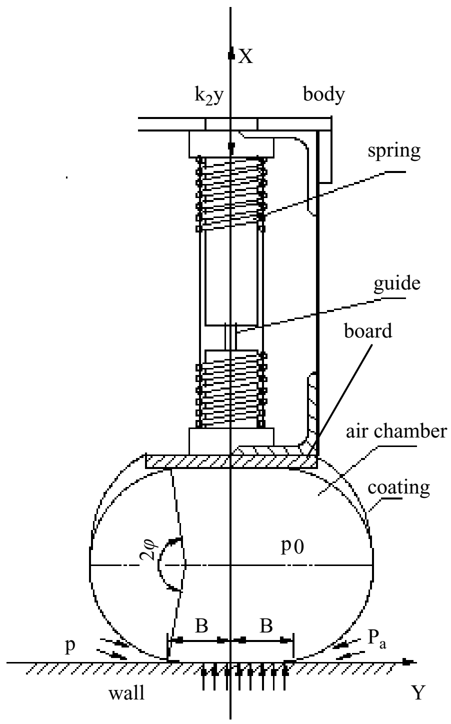

Fig. 3. The structure diagram of the sealing loop.

and have low friction. In order to realize the two requirements above, an air spring/regulating spring combination is adopted as the sealing mechanism, which is fixed around the sucker (Fig. 3). A board, an air chamber and a layer of coating constitute the air spring. The air chamber is used for the purpose of surface adaptation. To improve the load-carrying capacity of the robot, the coating is made up of composite material which is wearable and causes only small friction. On top of the air spring, there are twelve springs installed to add an appropriate pressure, so that not only the sealing is reliable, but also the touching force between the sealing loop and the wall surface can be controlled.

In order to ensure reliable sealing, the contact force between the air spring and the wall surface, σ_x, should be no smaller than the pressure difference inside and outside of the sucker $\triangle p_c$, that is:

$$\sigma_x \geq \Delta p_c \tag{8}$$

Where: σ_x and σ_y are the pressure forces in the x- and y-directions, respectively, between the air spring and the wall (Pa); $k' = \sigma_x/\sigma_y$ is a coefficient and is usually less than 1;

The composite rigidity of the sealing loop is:

$$k = \frac{nk_2k_1}{nk_2 + k_1} \tag{9}$$

where: k_1 is the rigidity of the air spring (N/m); k_2 is the rigidity of a single regulating spring (N/m); n is the number of regulating springs. Thus the rigidity of the air spring is:

$$k_1 = m\,(p_0 + p_a)\,(1+\beta)\,\frac{A_0^2}{V_0} - \alpha \cdot p_0 A_0 \tag{10}$$

where: m is the levity exponential; $2B$ is the effective contact width of the sealing loop(m); p_0, A_0, V_0 are the inside

Fig. 4. Photo of a remote-control-inspect wall-climbing robot.

pressure (P_a), the effective bearing area (m^2) and the cubage (m^3) of the air spring in the design position, respectively; r is the radius of the section of the air chamber in the design position (m); φ is the center angle (°) of its arc part.

Suppose that the rated compression amount in the y-direction of the whole sealing mechanism is y, then:

$$\sigma_y = ky/A_0 \tag{11}$$

Substituting (11) into (8), one can obtain:

$$k \geq \frac{\Delta p_c A_0}{k' y} \tag{12}$$

Eq. (12) is the condition that the composite spring rigidity of the sealing loop must be satisfied in order for the robot to adhere reliably to the wall. In Eq. (12), $\triangle p_c$ is supplied from Eq. (7); The rated compression amount, y, can be determined by the designer according to the structure of the robot; A_0 is decided by the structure of the sealing loop.

3. APPLICATION EXAMPLE 1: REMOTE-CONTROL, WALL-CLIMBING ROBOT FOR INSPECTION OF NUCLEAR STORAGE TANKS

Nuclear storage tanks need to be inspected regularly for fear of leakage. Because the conditions are extremely dangerous, a remote-control, wall-climbing robot with inspection devices and CCD is developed to examine the quality of the surface and the weld seams on the surface of the container in which nuclear waste material is stored. This is a complicated system. Besides the robot, there are also the carrier loader, the manipulator, the visual system, the safety system, the remote-control board and the flaw detector. The robot is transported to its destination by the carrier loader. The manipulator is responsible for moving the robot on and off the tanks. Because the tanks are welded by stainless steel, which is a non-magnetic-conductive material, the suction mode of the robot is chosen to be a negative pressure suction. Fig. 4 shows a photo of a remote-control, wall-climbing robot developed

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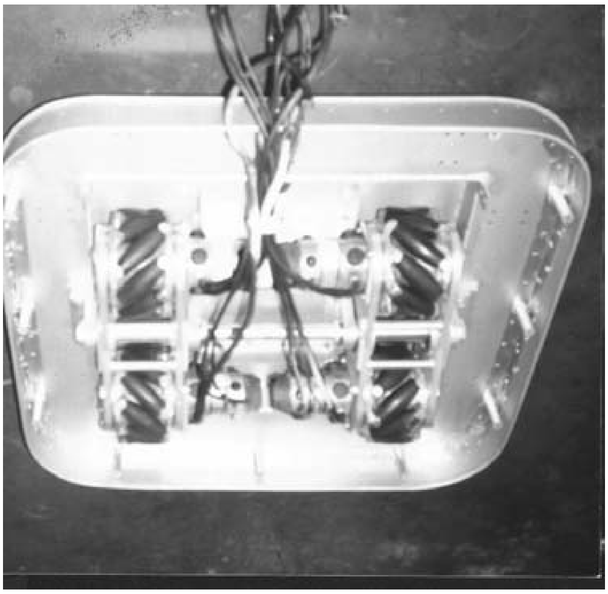

Fig. 5. Photo of four omni-directional wheels of the robot.

for this study. The tested prototype of the robot consists of the following sub-systems

a) Wall-climbing robot subsystem: it adopts the suction mode of a single suction cup to hold an inspecting instrument and the visual devices to inspect the surface of tanks. In order to make the robot move precisely on the surface, four omni-directional wheels are used as the driving mechanism. Fig. 5 shows the photo of the four omni-directional wheels.
b) Remote-control subsystem: it is a two-level computer configuration. Fig. 6 is the block diagram of the control system. A master computer works on the route layout of the robot. The slave computer takes the STD Bus as the kernel, and through programming, controls the rotation speed and rotation direction of the servomotor on the wheels, so that it realizes omni-directional moving of the robot on the surface. In order to make the robot move in stable lines on the surface, it adopts an inclinometer (LUCAS) as the pose-emendating sensor to make the driving mechanism of the robot realize the closed-loop control for posing and moving accurately along the weld seam, so as to inspect precisely the weld seam.[11] The wire remote distance is no smaller than 100 meters. Fig. 7 shows the structure of posture control.
c) Carrier loader subsystem: it transports all the devices needed for inspection to the destination from the control center, and then carries them back after the inspection.
d) Ultrasonic inspecting subsystem: it is carried by the robot to detect the flaws and to measure the thickness of the tank surface.
e) Manipulator subsystem: it is installed on the carrier loader. It takes the robot and its attachments on the tank before the inspection, and takes off the robot and its attachments after the inspection.
f) Safety subsystem: it is installed on the carrier loader. A safety rope drags the robot for the sake of sloping the robot and its attachments falling from the tank surface.
g) Visual subsystem: it is installed on both the carrier loader and the robot. Its task is to transfer the visual message in the moving process of the carrier loader and the inspecting process to the remote-control center.

Major technical parameters of the remote-control-inspect wall-climbing robot indices are as follows:

(i) Travelling speed: 0–2 m/min (adjustable);
(ii) Orientation precision: ± 2 mm (based on tests, ensuring to meet the accurateness and fidelity of ultrasonic detecting flaw for weld seam);
(iii) Thickness tolerance of ultrasonic measure: ± 1 mm;
(iv) Weight of robot: < 22 kg;
(v) Maximum payload: 150 N.

4. APPLICATION EXAMPLE 2: WALL-CLIMBING ROBOT SYSTEM FOR CLEANING HIGH-RISE BUILDINGS

Another appropriate application field of wall-climbing robots is the maintenance of the outside of high-rise buildings. Up to now, the cleaning of most high buildings is done manually with the aid of cranes. It is a dangerous and time-consuming job. Hence a wall-climbing robot is developed to replace people in order to clean automatically. Considering the walls of most high buildings are of ceramic tile or glass surfaces (a certain percentage of walls are smooth, without apparent roughness and unevenless at the glass

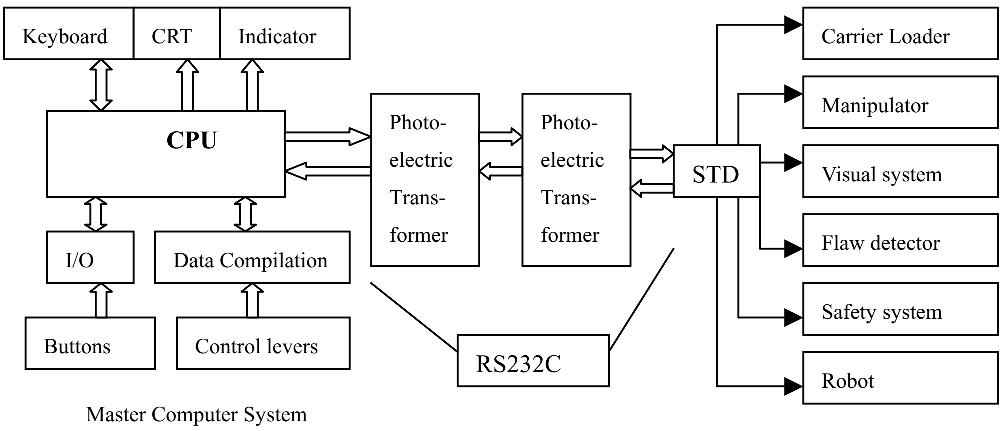

Fig. 6. The block diagram of the control system.

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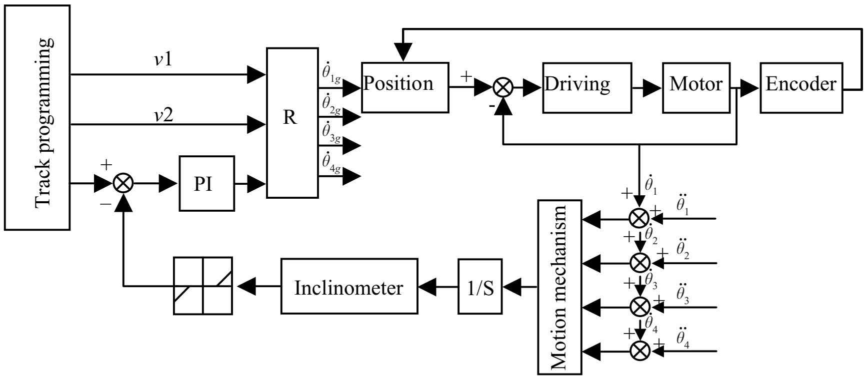

Fig. 7. Structure of posture control.

surfaces), which are non-magnetic conductive materials, and on which large gap exists, it is appropriate to develop a wall-climbing robot with a single suction cup to clean the walls. Fig. 8 & Fig. 9 are live photo shots of the wall-climbing robot developed during the study operating on the wall. Cleaning operation showed that the efficiency could reach 180 ∼ 240 m^2/h, which is 3 ∼ 4 times of that of a proficient worker, and also showed that the resulted cleanness was at the same level of that of manual work.[12,13]

The whole system consists of a cleaning robot, a safety device and a control subsystem. Each subsystem is introduced as follows:

a) Cleaning robot: it is the core of whole robot system, composed of a climbing mechanism, a cleaning mechanism, a water-supplying and a sewage-withdrawing mechanism, etc. To simplify the system, a two-wheel mechanism is adopted in place of the omni-directional vehicle. Meanwhile, in order to ensure that the robot does not incline in the process of moving up and down on the wall surface, an inclinometer is employed to ensure closed-loop pose control.

For the water will flow downward automatically in the process, it is arranged for the robot to clean the wall surface from top to bottom. The cleaning mechanism, which consists of eight muzzles, a brush, a scraper, a water pump and a sewage-withdrawing mechanism, is installed below the robot. Scour, mixed with water in some proportion, is supplied by a pump from the top of the building to the robot.

According to tests, the cleaning process, i.e., brushing first, swilling then, scraping last, was proven to be successful. In addition, owing to the usage of a sewage-withdrawing mechanism, there is no apparent sewage washing down in the process and no environmental pollution.

b) Safety device is one of the indispensable parts. The safety device, mounted on the top of buildings, has two functions: protecting the robot from falling when unpredictable loss of power or excessive gap on the wall surface lead to the situation that the negative pressure in the sucker cannot be maintained; and sharing the increasing weight of the control cables with increasing height to ensure the payload to be within the design field, and to enable the robot to climb on the wall as high as it can.

Fig. 8. Photo of robot cleaning the ceramic tile surface.

Fig. 9. Photo of robot cleaning the glass surface.

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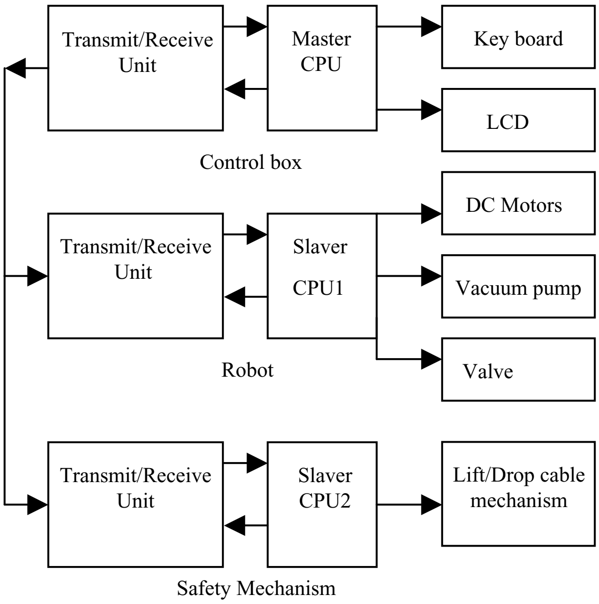

Fig. 10. The block diagram of the control system.

c) Control subsystem: it consists of three parts: a cleaning robot controller, a safety device controller and a ground remote controller. The ground remote controller sends instructions to the cleaning robot controller and the safety device controller through a wireless connection, and instructs the two controllers performing the cleaning task in a programmed sequence. A transducer controls the rotating speed of the windlass on the safety device, and the tension control system of the safety device controls the windlass to follow the robot. Thus, the robot can be used to clean walls at different speeds according to local condition of the walls. Fig. 10 is the block diagram of the control system.

Main technical parameters are as follows:

(i) Moving speed: 0–8 m/min (continually adjustable);
(ii) Method of cleaning: brushing, swilling, scraping;
(iii) Efficiency of cleaning: $180 \sim 240\,m^2/h$;
(iv) Control mode: wireless remote control;
(v) Climbing height: < 100 m;
(vi) Weight of robot: < 27 kg.

5. CONCLUSION

As discussed above, wall-climbing robots with a single suction cup have desirable characteristics, such as simple structure, flexible movement, convenient control, and are suitable for wall surfaces made of different materials. Therefore, the exploitation of this kind of wall-climbing robots has wide prospects. In the recent past, the authors have been working on it. Specifically, satisfactory progress has been made regarding the wall-cleaning robots, which is slated for manufacture at present.

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