Robotica (2024), **42**, pp. 962–976
doi:10.1017/S026357472300173X

RESEARCH ARTICLE

Design and analysis of a wall-climbing robot with passive compliant mechanisms to adapt variable curvatures walls

Yifeng Song[1,2], Zhenyu Yang[1,2,3], Yong Chang[1,2], Hui Yuan[1,2,4] and Song Lin[1,2,3]

[1]State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, 110016, China, [2]Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang, 110169, China, [3]University of Chinese Academy of Sciences, Beijing, 100049, China, and [4]School of Mechanical Engineering and Automation, Northeastern University, Shenyang, 110004, China
Corresponding author: Yifeng Song; Email: songyifeng@sia.cn

Received: 1 June 2023; **Revised:** 11 November 2023; **Accepted:** 28 November 2023; **First published online:** 5 February 2024

Keywords: variable curvature; curvature adaptive; passive compliant mechanism; wall-climbing robot

Abstract

Motivated by practical applications of inspection and maintenance, we have developed a wall-climbing robot with passive compliant mechanisms that can autonomously adapt to curved surfaces. At first, this paper presents two failure modes of the traditional wall-climbing robot on the variable curvature wall surface and further introduces the designed passive compliant wall-climbing robot in detail. Then, the motion mechanism of the passive compliant wall-climbing robot on the curved surface is analyzed from stable adsorption conditions, parameter design process, and force analysis. At last, a series of experiments have been carried out on load capability and curved surface adaptability based on a developed principle prototype. The experimental results indicated that the wall-climbing robot with passive compliant mechanisms can effectively promote both adsorption stability and adaptability to variable curvatures.

1. Introduction

With the continuous breakthrough of human engineering ability, there have been appeared a large number scenarios of inspection and maintenance, which are high-risk and high-intensity, in the nuclear industry, transportation, shipbuilding, and other industries. The wall-climbing robot was proposed as a novel emerging technology that would release humans from cleaning [1], nondestructive testing [2], painting [3], and maintenance [4] in vertical wall environments that are difficult for people to work.

In 1966, Akiri developed the first wall-climbing robot using vacuum suction to move on vertical walls [5, 6]. After that, more and more research institutions, including Boston Power [7] and Zurich Technology [8], have researched wall-climbing robots. Many adsorption technologies have been explored: vacuum suction [9, 10], magnetic attraction [11], and bionic adsorption [12, 16], and each technology has advantages and disadvantages. Vacuum suction is the closest to the application requirements due to its simple structure, easy control, and ability to adapt to different types of material surfaces. Currently, wall-climbing robots have realized stable adsorption and operation on vertical flats. Yuan *et al.* [13, 14] proposed a rolling sealed wall-climbing robot, which realized stable adsorption and all-around flexible motion on vertical surfaces by changing the seal skirt's friction from sliding friction to rolling friction. Daniel *et al.* [15] have designed a new wall-climbing robot whose vacuum adsorption system was composed of seven small controllable vacuum adsorption chambers, which can effectively prevent the robot from slipping or falling due to partial vacuum leakage and realize the robot's security and speedy movement on rough surfaces.

However, wall-climbing robots' adaptability and stability on variable curvature wall surfaces are remaining challenges. It is very difficult for the wall-climbing robot to have mobility on different wall surfaces, such as tank, propeller, and shell surfaces. Wang *et al.* [17] have designed a double frame mechanism, which has the relative rotation and mutual sliding functions of each frame layer, that can achieve self-adaptation on walls with asymmetrical changes in curvature. Guan *et al.* [18] have designed a 5-DoF biped wall-climbing robot with six vacuum suctions. The robot can implement transition between walls and stable adaptation to curvature wall surface changes. Fujita *et al.* [19] have created an active rotating mechanism containing a tilting mechanism, which enables smooth robot movement on curvature walls through the orderly rotation of the mechanism in conjunction with a vacuum air cushion. Those active adjusting mechanisms improve the wall-climbing robot's adaptability to variable curvature wall surfaces. However, the added active adjustment mechanisms lead to complexity in the wall-climbing robot's mechanical and control systems and reduce the robot's load capacity and movement speed.

Alternatively, the passive compliance mechanism has features over the active adjusting mechanism for wall-climbing robots. Many researchers have studied this mechanism for wall-climbing and developed prototypes. Shang *et al.* [20] designed an adsorption device with a rotating mechanism with three-point non-collinear support. Through the force change between the vacuum sucker and the wall, the rotating mechanism rotates independently to realize the adaptation of variable curvature wall surfaces. A compliant mechanism containing an asymmetric four-bar mechanism was created [21]. It achieves self-adaptation to walls of variable curvatures through the rotation of a trapezoidal four-bar mechanism and the deformation of the flexure mechanism. The deformation of passive compliant mechanisms is uncontrollable, which increases the mechanical system's instability and decreases the adsorption stability and load capacity of wall-climbing robots.

Passive compliant mechanisms has not been better used in conventional wall-climbing robots, and its mobility has not been fully explored and demonstrated. Based on the above analysis of the wall-climbing robot's mechanism and an in-depth study of the passive compliance mechanism, we designed a novel passive compliant wall-climbing robot with better mobility, simpler structure, and easier control than traditional wall-climbing robots. As will be known in the following sections, the robot has good climbing ability, variable curvature adaptability, and load capacity.

The rest of this paper is organized as follows. Section 2 describes the wall-climbing robot facing current challenges and main failure modes of lack of adaptability and passive compliant wall-climbing robot's structural design and surface adaptation process. Section 3 elaborates on the state analysis of the passive compliant wall-climbing robot on the curved surface based on the three aspects of stable adsorption conditions, parameter design process, and force analysis. Section 4 describes the prototype and related experiments of the passive compliant wall-climbing robot. Section 5 provides conclusions of the current work.

2. Passive compliant mechanism design for the curved surface climbing

2.1. Challenges of curved surface adsorption

In the typical design, the wall-climbing robot is composed of a sealing component, a mobile module, a suction chamber, a negative pressure generator, and a control module. As shown in Fig. 1(a), while the robot is working on a flat surface, the sealing component is tightly attached to the wall surface and a negative pressure environment can be created by the negative pressure generator in the suction chamber. The mobile module is designed to match the sealing component, which means both of them can be attached to the wall simultaneously.

The sealing components are made of sponge-like materials and have excellent elasticity. Through the elastic deformation of the sealing component, the robot can maintain the sealing state of the suction chamber on a slightly curved surface, and on the other hand, the moving module keeps attaching to the surface to make the robot's locomotion, as shown in Fig. 1(b).

The state of a traditional wall-climbing robot with an integrated rigid body structure design on a curved surface will be discussed separately based on convex and concave surfaces.

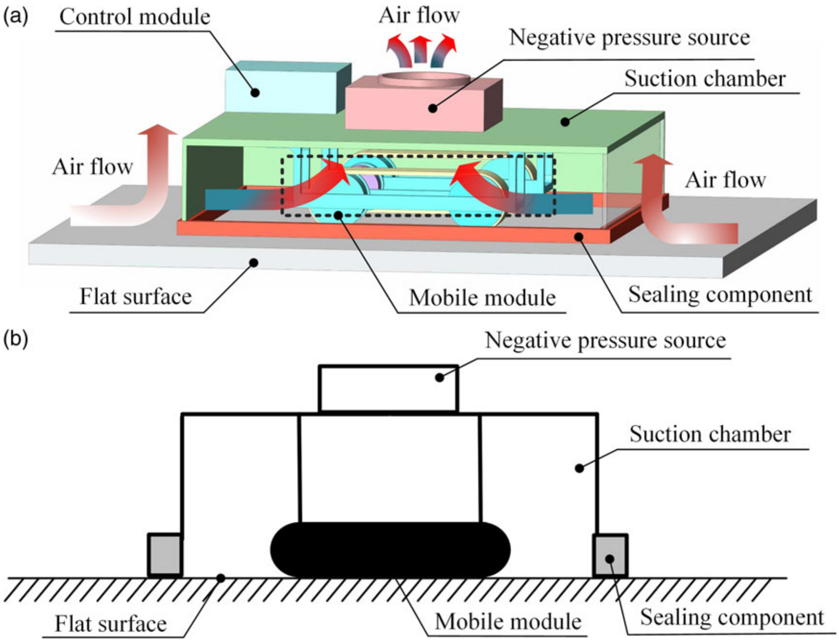

Figure 1. *(a) The wall adsorption process of the traditional wall-climbing robot. (b) The schematic diagram of the traditional wall-climbing robot mechanism.*

For the concave surface, the sealing components of the traditional wall-climbing robot adhere to the concave surface and the negative pressure environment can be formed in the suction chamber. However, the mobile module cannot fit with the wall surface due to the influence of the curved surface, as shown in Fig. 2(a). It means that although the robot can adhere to the surface, it cannot move on the surface due to the failure of the mobile module.

For the convex surface, the mobile module of the traditional wall-climbing robot adheres to the surface. However, the sealing component cannot adhere to the wall surface, which results in the leakage state of the suction chamber. As shown in Fig. 2(b), due to the leakage, the robot will not be able to adsorb on the surface and fall off the wall.

Therefore, the challenge of robot design on curved surfaces is to adjust the position relationship between the sealing component and the mobile module properly and maintain adsorption and mobility capability simultaneously. Compared to adding active mechanisms to adjust the position relationship aforementioned, a passive mechanism adjustment based on the environmental features of curved surfaces will improve the simplicity, reliability, and practicality of the wall-climbing robot system.

It should be noted although robots can adsorb on curved surfaces by extending the height of the sealing component, this method only applies to low-curvature walls rather than high-curvature surfaces. This is because excessively extending the sealing component will not only greatly increase the frictional resistance during the robot's movement as shown in Fig. 3(a) but also cause the leakage on the side of the suction chamber as shown in Fig. 3(b).

2.2. Mechanism design

As the sealing components and the drive modules of the traditional wall-climbing robots are both rigidly connected to the frame, such robots cannot always keep their drive wheels well fitted to the wall surface, which has variable and large curvature.

In this paper, we present a novel wall-climbing robot with a compliant adjusting module to adjust the position between the mobile modules and sealing components to solve the movement failure and

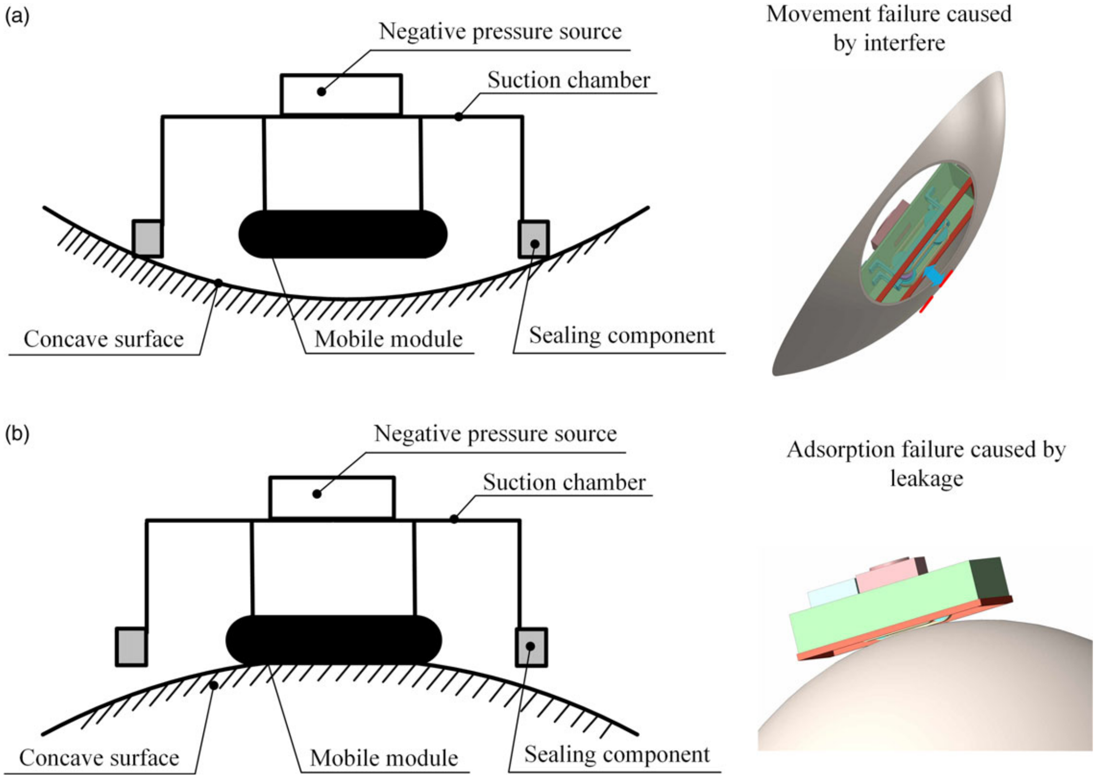

__Figure 2.__ (a) Movement failure caused by interference of the traditional wall-climbing. (b) Adsorption failure caused by leakage of the traditional wall-climbing robot mechanism.

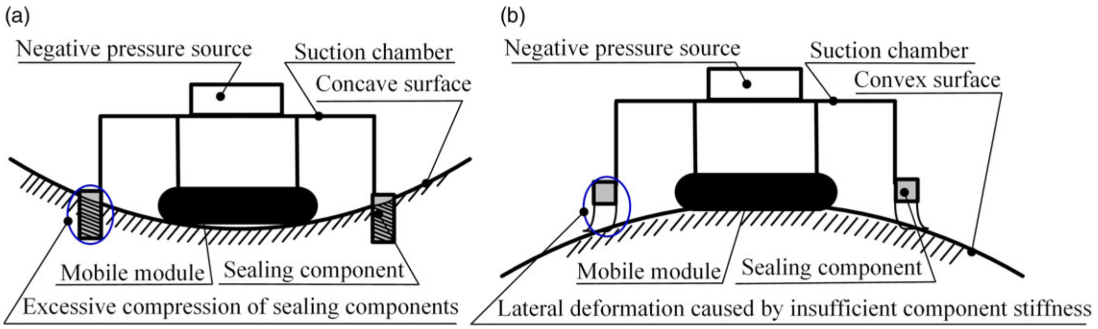

__Figure 3.__ (a) Movement failure: the excessive compression of the sealing component on the concave surface leads to increased resistance, which could cause movement failure. (b) Adsorption failure: the extension of the sealing component will reduce the stiffness of the component and cause lateral deformation, which could cause leakage or even adsorption failure.

adsorption failure on curved surfaces. Figure 4 illustrates the way that the robot adapts to various curvature wall surfaces by using the compliant module in different deformation states. In Fig. 4(a), the sealing component is in a limited compression state on a flat wall surface. The compliant adjusting module's compression deformation state is half-compressed. When the curvature of the wall surface increases [see Fig. 4(b)], the compliant adjusting module will be deformed to varying degrees to adapt to the change of wall curvature and ensure that the sealing component can contact the wall to prevent the leakage of

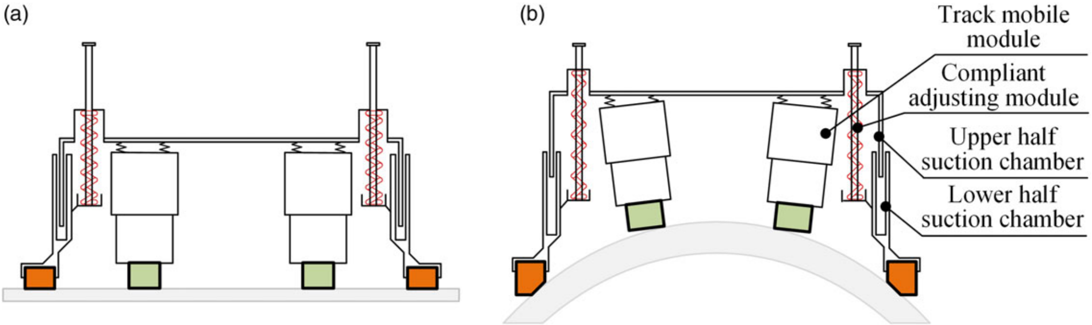

Figure 4. *(a) The wall-climb robot moves on the flat wall surface. (b) The wall-climb robot moves on the wall surface with large curvature.*

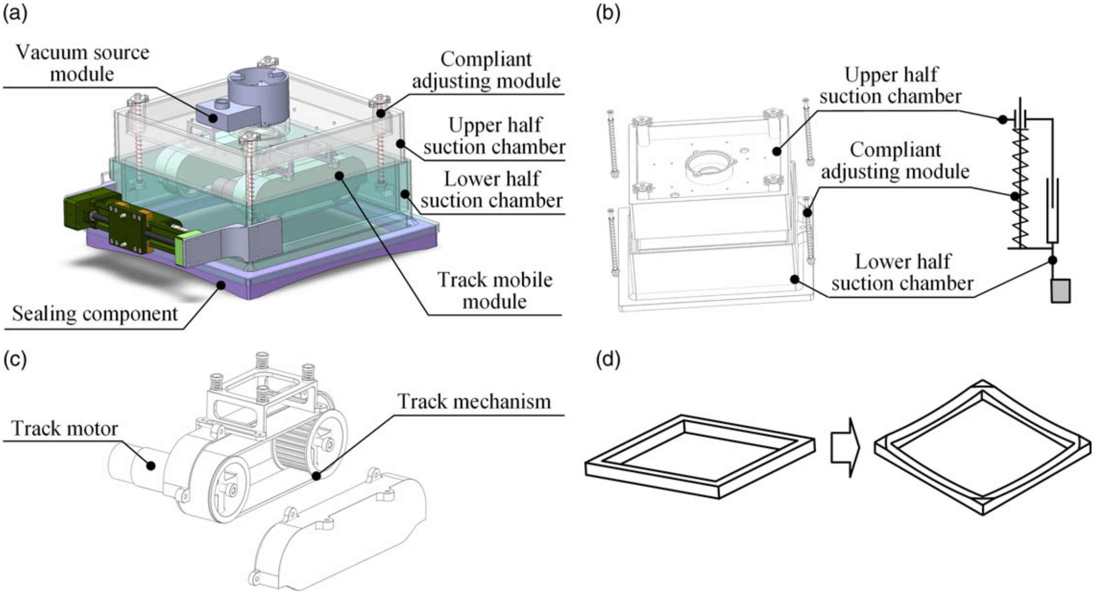

Figure 5. *Mechanical design of the passive compliant wall-climbing robot. (a) Mechanical configuration of passive compliant wall-climbing robot. (b) Vacuum suction and compliant adjusting module. (c) Track mobile module. (d) Sealing component.*

negative pressure. On the other hand, the adsorption force increases with the pressure difference between the inside and outside of the suction chamber increases.

As the compliant adjusting module is gradually compressed, the mobile module installed on the upper half suction chamber moves to the wall surface until the track of the mobile module can fully contact with the wall surface. As a result, during the moving process, the compliant mechanisms make the limited vacuum adsorption force on the track, providing enough traction for the robot’s movement.

The mechanical design of the wall-climbing robot with a passive compliant mechanism has been carried out in detail to achieve stable adsorption and smooth movement on the unstructured walls of variable curvature.

As shown in Fig. 5(a), the robot is mainly composed of a sealing component, two track mobile modules, a compliant adjusting module, a suction chamber, a power module, a vacuum source module, and control system. The suction chamber of the robot is comprised of an upper half and a lower half suction chamber, and four evenly distributed compliant adjusting modules, which connect the upper and lower

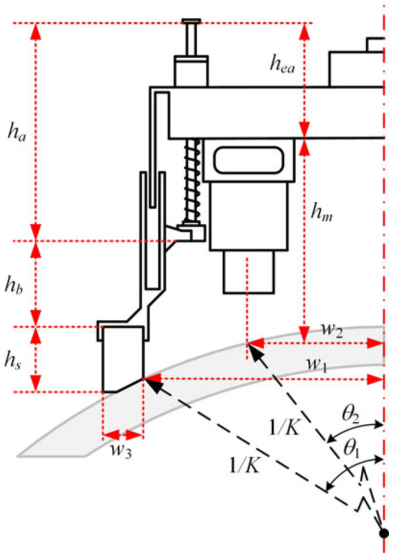

Figure 6. *Geometric relationship during stable adsorption of the robot.*

suction chamber [see Fig. 5(b)]. Each compliant adjusting module includes a spring and guiding axis. The spring compliant adjusting module can be deformed to make the sealing component adhere to the wall when the robot is moving on curved wall surfaces. The track mobile module and vacuum source module are installed in the upper half suction chamber. As illustrated in Fig. 5(c), the track mobile module consists of a passive adjusting mechanism, track motor, and track mechanism. The sealing component is made of wear-resistant cloth and high-elastic materials and is installed under the lower half suction chamber. The shape of the sealing component is designed to adapt to the sphere surface as shown in Fig. 5(d) to prevent air pressure leakage during the robot's movement on the wall surface.

3. State analysis of the passive compliant wall-climbing robot on a curved surface

3.1. Stable adsorption conditions

The structural parameters of the passive compliant mechanism have a great influence on the robot's adaptability to the variable curvature surfaces. For the structural parameters of the passive compliant mechanism, this section analyzes the stable adsorption conditions of the passive compliant wall-climbing robot on the variable curvature wall. As shown in Fig. 6, according to the geometric relationship that the robot needs to satisfy on the variable curvature wall, the position closed-loop equation of the robot's stable adsorption state on the variable curvature wall can be obtained

$$\sqrt{\left(\frac{1}{K}\right)^2 - {w_2}^2} + h_m + h_{ea} = \sqrt{\left(\frac{1}{K}\right)^2 - {w_1}^2} + h_a - \Delta\delta + h_b + h_s - \Delta\varepsilon \tag{1}$$

where $2w_1$ is the width of the suction chamber, $2w_2$ is the width between the two mobile tracks, h_a is the height of the compliant adjusting module, h_b is the basic height of the suction chamber, h_{ea} is the distance that compliant adjusting module higher than the suction chamber, h_m is the higher off the track, h_s is the height of the compliant sealing component, $\Delta\delta$ is the elastic deformation of the compliant adjusting module, and $\Delta\varepsilon$ is the elastic deformation of the compliant sealing component. In the design process, those parameters were determined on whether the robot can successfully adhere to the series of surfaces with curvature variations.

In Fig. 7, $A_i (i = 1, 2, 3, 4)$ is the contact point between the passive compliant sealing component and the wall surface in the initial state, and $B_i (i = 1, 2, 3, 4)$ is the contact point between the outermost part

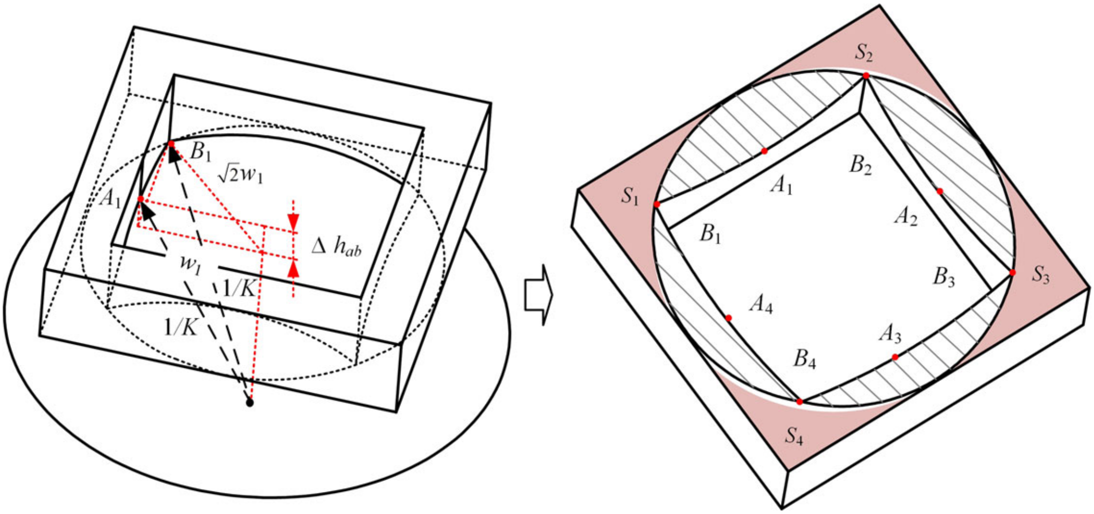

Figure 7. *The minimum deformation of the sealing component on the spherical surface.*

of the passive compliant sealing mechanism and the wall surface while the robot is stably adsorbed. $S_i(i = 1, 2, 3, 4)$ is the projection of the gap area between the suction chamber and the wall surface in the initial state.

As shown in Fig. 7, the passive compliant sealing mechanism's primary function is to realize the robot's conversion from $A_i \rightarrow B_i$ adsorption through its passive, compliant compression deformation. This process can effectively reduce the leakage of negative pressure and provide sufficient and stable adsorption force by eliminating the gap S_i between the robot and the surface to realize the robot's self-adaptation to the wall. So in order to ensure that the passive compliant adjustment mechanism can complete the transformation of the robot from $A_i \rightarrow B_i$ adsorption state, realize the adaptation of the passive compliant sealing mechanism to the wall surface, and ensure the stability of negative pressure adsorption, the maximum deformation $\Delta\varepsilon_{\max}$ of the sealing component needs to meet the following condition:

$$\Delta\varepsilon_{\max} \geq \Delta h_{AB} = \sqrt{\left(\frac{1}{K}\right)^2 - w_1^2} - \sqrt{\left(\frac{1}{K}\right)^2 - 2w_1^2} \tag{2}$$

According to equation (2), the compression Δh_{AB} of the passive compliant sealing mechanism decreases with the decrease of the wall curvature K, and when $\Delta h_{AB} = \Delta\varepsilon_{\max}$, the critical curvature K of the surface that the robot can adapt to is the maximum curvature K_1.

In summary, the prerequisites for stable adsorption of wall-climbing robots are

$$\begin{cases} \sqrt{\left(\frac{1}{K}\right)^2 - {w_2}^2} + h_m + h_{ea} = \sqrt{\left(\frac{1}{K}\right)^2 - {w_1}^2} + h_a - \Delta\delta + h_b + h_s - \Delta\varepsilon \\ \Delta\varepsilon_{\max} \geq \Delta h_{AB} = \sqrt{\left(\frac{1}{K}\right)^2 - w_1^2} - \sqrt{\left(\frac{1}{K}\right)^2 - 2w_1^2} \end{cases} \tag{3}$$

3.2. Mechanical parameter design process

As mentioned in Section 2.1, there could be an adsorption failure due to lateral instability of the sealing component only by extending the height of the sealing component to improve the robot's curved surface adaptation. In this case, the passive compliant adjustment mechanism is introduced to vanish the lateral instability of the sealing component and realize the self-adaptation of the moving mechanism to the wall surface for the robot. When the robot adheres to a curved surface, the deformation of the sealing component and compliant mechanism meets the following equation:

$$h_a - \Delta\delta = \sqrt{\left(\frac{1}{K}\right)^2 - w_2{}^2} - \sqrt{\left(\frac{1}{K}\right)^2 - w_1{}^2} + h_m + h_{ea} - h_b - h_s + \Delta\varepsilon \tag{4}$$

According to equation (4), after the structural parameters of the wall-climbing robot are determined, the working length h_a and the maximum compression deformation $\Delta\delta_{\max}$ of the passive adjustment mechanism determine the curvature range of the wall that the wall-climbing robot can adapt. While the passive adjustment mechanism's compression amount $\Delta\delta = 0$, the wall curvature K_2 is the maximum curvature that can be adapted by the robot. While the compression amount of the passive adjustment mechanism $\Delta\delta = ah_a$, the wall curvature K_3 is the minimum curvature that can be adapted.

When the curvature of the wall surfaces is $K = K_2$:

$$\begin{cases} \Delta\delta = \Delta\delta_{\min} = 0 \\ \Delta\varepsilon = \Delta\varepsilon_{\max} \end{cases} \tag{5}$$

When the curvature of the wall surfaces is $K = K_3$:

$$\begin{cases} \Delta\delta = \Delta\delta_{\max} = ah_a \\ \Delta\varepsilon = \Delta h_{AB} \end{cases} \tag{6}$$

According to equations (2), (4), (5), (6), can be obtained :

$$\begin{cases} \cos\theta_1 = K_2 w_2, \cos\theta_2 = K_2 w_1 \\ \cos\alpha_1 = K_3 w_2, \cos\alpha_2 = K_3 w_1 \end{cases} \tag{7}$$

K_2 and K_3 can be expressed as :

$$\begin{cases} K_2 = \dfrac{\sin\theta_1 - \sin\theta_2}{h_a + (1-b)\,h_s + h_b - h_{ea} - h_m} \\[2ex] K_3 = \dfrac{\sin\alpha_1 - \sin\alpha_2}{(1-a)\,h_a + h_b + h_s - h_{ea} - h_m - \Delta h_{AB}} \end{cases} \tag{8}$$

From equations (4), (8), it can be obtained that :

$$\frac{\sin\theta_1 - \sin\theta_2}{K_2} - \frac{\sin\alpha_1 - \sin\alpha_2}{K_3} = ah_a - bh_s + \Delta h_{AB} \tag{9}$$

According to equations (8), (9), increasing the h_a and $\Delta\delta_{\max}$ will help improve the surface's adaptability. More importantly, reducing the h_s and $\Delta\varepsilon_{\max}$ is beneficial to improve the adsorption stability and does not affect the robot's adaptability to the curved surface. In the robot system, the passive compliant sealing machine is mainly used for sealing between the contact surfaces. The passive compliant adjustment mechanism completes the adaptive adjustment of the robot's moving mechanism to the wall surface. Moreover, the range of curvature that the robot can adapt to the wall is determined by the $\Delta\delta_{\max}$. More attention is paid to that the given $[K_{\min}, K_{\max}]$ can be satisfied by multiple sets of h_m and h_b. Figure 8 shows the detailed calculation steps of the compliant mechanism parameters, which are done iteratively based on the position closed-loop equation and force equilibrium equation.

3.3. Force analysis

In the process of movement, the friction force generated by the adsorption force acting on the passive compliant sealing component is the resistance against the robot's movement, while the friction force generated by the adsorption force acting on the moving mechanism is the traction force. Therefore, the

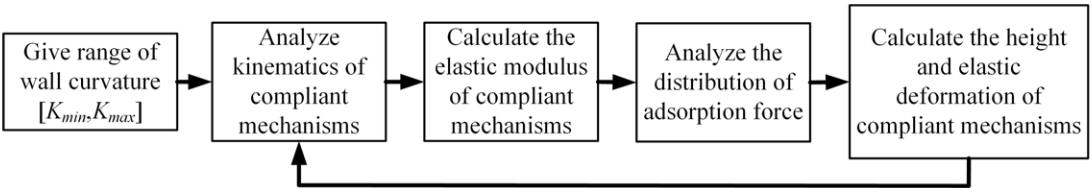

Figure 8. *Structural parameter optimization of the passive compliant wall-climbing robot.*

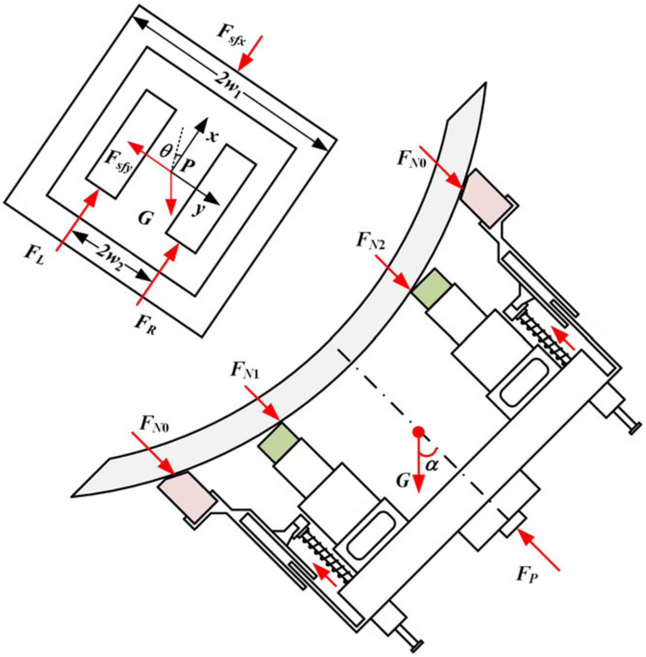

Figure 9. *Force analysis of robot adsorbed on curved surface.*

proportion of the adsorption force acting on the passive compliant sealing mechanism and the moving mechanism directly affects the wall-climbing robot's adsorption stability, dynamic performance, and load capacity. As shown in Fig. 9, the state overturning or slipping is selected as a severe working condition, and the robot's force when doing a straight line is analyzed.

The coordinate $P-xy$ system is established with the projection P of the geometric center of the robot on the wall as the origin, the forward direction of the robot as the x axis, and the direction perpendicular to the forward direction of the robot as the y axis. It obtained the force equilibrium equations of the wall-climbing robot.

$$\begin{cases} \Sigma F_x = F_L + F_R - F_{sfx} - G\sin\alpha\cos\theta = 0 \\ \Sigma F_y = G\sin\alpha\sin\theta - F_{sfy} = 0 \\ \Sigma F_z = F_{N1} + F_{N2} + F_{N0} + G\cos\alpha - F_P = 0 \\ \Sigma M_x = -F_{N1}w_2 + F_{N2}w_2 - Gh_G\sin\alpha = 0 \end{cases} \tag{10}$$

where h_G is the distance between center of gravity of the robot and the contact surface of the wheel. The adsorption force ratio on the passive compliant sealing mechanism is k_s.

$$\begin{cases} f_{sfx} = \mu_1 F_{N0} \\ F_{N0} = k_s F_P = \Delta h_{AB} E \end{cases} \tag{11}$$

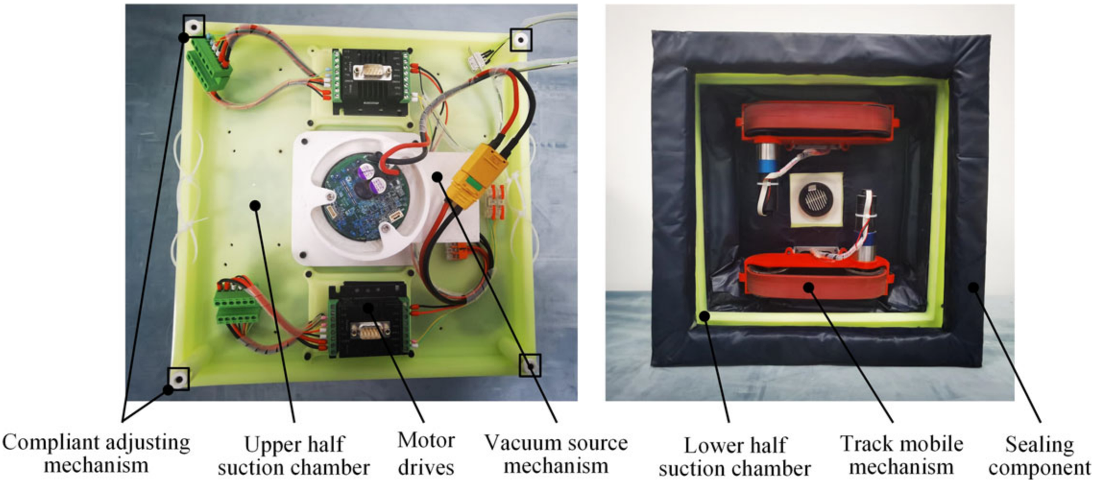

Figure 10. *Principle prototype.*

When the robot is doing uniform motion, it is assumed there is no slip in the lateral direction, and the traction force provided by the left and right tracks is the same.

$$\begin{cases} F_{N1} = \dfrac{1-k_s}{2}F_P + \dfrac{Gh_G \sin\alpha}{4w_2} \\ F_{N2} = \dfrac{1-k_s}{2}F_P - \dfrac{Gh_G \sin\alpha}{4w_2} \end{cases} \tag{12}$$

We can obtain the following equation by coulomb friction:

$$\begin{cases} F_R = \mu_2 F_{N1} \\ F_L = \mu_2 F_{N2} \end{cases} \tag{13}$$

where μ_2 is the static friction coefficient between the surface and the track. Through adding the passive compliant adjustment mechanism, the deformation Δh_{AB} of the passive compliance sealing component decreases, so that F_{N0} decreases, thereby reducing the friction resistance f_{sfx} and improving the adsorption stability. At the same time, the decrease of F_{N0} means the decrease of k_s, so the positive pressure F_{N1} and F_{N2} increase. It can be seen from the above that reducing f_{sfx} and increasing positive pressure F_{N1} and F_{N2} can increase the traction F_R and F_L and improve the dynamic performance and load capacity of the robot.

4. Experiments

4.1. Principle prototype

Based on the above analysis, the robot with passive compliant and negative pressure is developed, as shown in Fig. 10. The robot is equipped with a centrifugal fan to generate the negative pressure adsorption force. A layer of sealing component in the adsorption chamber ensures the gas tightness of the suction chamber. The passive compliant adjusting mechanism includes four guiding shafts and four springs distributed around the suction chamber, which are used to connect the upper and lower suction chambers. By changing the height and spring stiffness of the passive compliant mechanism, the adaptive range of the robot to the curved surface is changed. The track mobile mechanism is driven by T-type synchronous belts, and the surface of the synchronous belt is coated with 20 mm thick rubber to increase the friction coefficient between the track and the wall. The relevant parameters of the passive compliant wall-climbing robot are shown in Table I.

Table I. *The parameters of the principle prototype.*

Program	Dimension (mm)
Size of vacuum suction chamber ($2w_1 \times 2w_1$)	300×300
Height of the compliant adjusting module (h_a)	110
Elastic deformation of the compliant adjusting module ($\Delta\delta_{\max}$)	70
Height of compliant sealing component (h_s)	40
Elastic deformation of the compliant sealing component ($\Delta\varepsilon_{\max}$)	20
Height of track module (h_m)	50

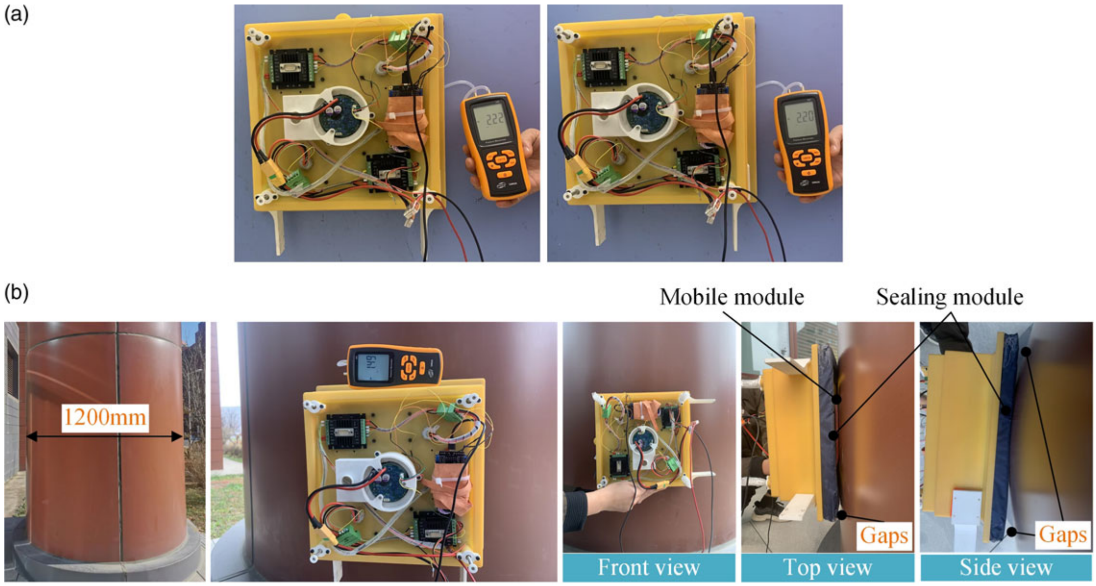

Figure 11. *Adsorption capacity comparison with traditional wall-climbing robot. (a) Flat surface. (b) Cylinder surface.*

The principle prototype is placed in the natural environment of a plane, cylinder, and sphere, respectively, for load capacity and variable curvature wall adaptive motion test research.

4.2. Adsorption capacity test

Test A: To verify the adaptability of the prototype to the curved surfaces, two sets of comparative experiments were carried out between the robot with and without the compliant adjusting module.

The first set of adsorption experiments was carried out on flat and cylinder surfaces with the developed robot with the compliant adjusting module, as shown in Fig. 11(a). The negative pressure state was measured by a manometer inserted into the adsorption chamber while the robot was in a stable adsorption state. The pressure in the negative chamber is 2.22 kpa on a flat surface and 1.5 kpa on a curved surface with a 600 mm curvature radius. It can be observed that the robot maintained stable adsorption on the cylindrical surface, despite the decrease of the negative pressure over 30%. The decrease in negative pressure is caused by the reduction of the effective sealing area of the sealing skirt due to the influence of the curved surface.

In the other set of adsorption experiments, we fixed the upper and lower suction chambers of the robot to disable the compliant adjusting module and kept the sealing component and the track mobile module in the same plane, which makes the robot with the traditional wall-climbing robot mechanism

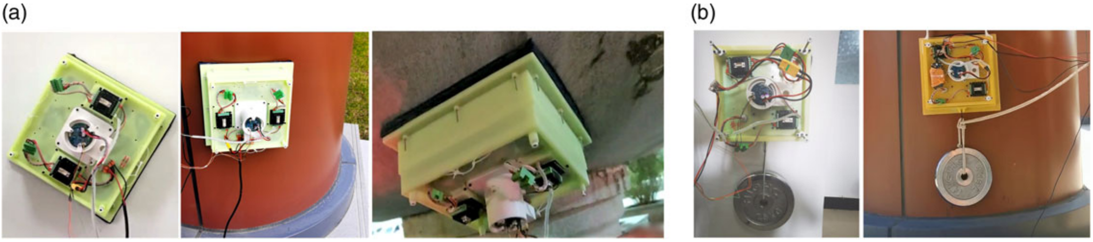

Figure 12. *(a) The adsorption experiments of the robot on the plane, cylindrical surface, and spherical surface. (b) The load experiment of the robot on the plane and cylindrical surface.*

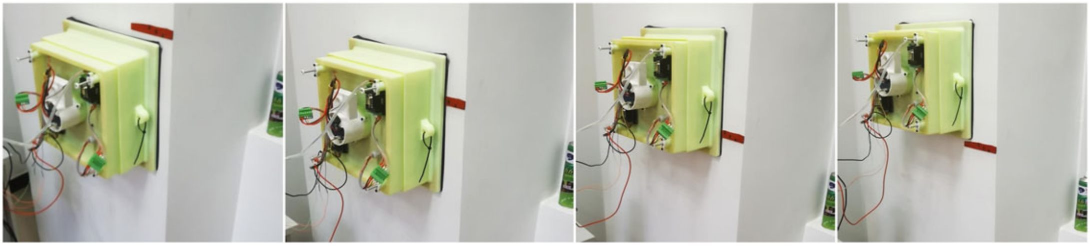

Figure 13. *Motion and obstacle crossing experiments of the robot on a vertical flat wall.*

as shown in Fig. 1. The experiments were also carried out on both the flat and cylindrical surfaces. The pressure in the negative chamber is 2.2 kpa for a flat surface, which is nearly the same as with the compliant adjusting module. In contrast, the sealing component could not fit the cylindrical surface due to the absence of the compliant adjusting module, and adsorption failure caused by leakage as shown in Fig. 11(b) has occurred.

Test B: The adsorption experiments of plane, cylinder, and sphere were carried out, as shown in Fig. 12(a); the robot can adsorb on the plane, cylinder, and sphere walls at any position and posture which shows good surface adaptability. Moreover, the deformation of the passive compliant module is larger than the sealing component, which means the robot mainly adapts to curved surfaces through the compliant mechanisms rather than the sealing component.

As shown in Fig. 12(b), the load capacity of the robot under different curvature walls is tested. The robot can suffer a 7.5 kg load without slipping in the plane, and cylinder walls. As the load increases to 9 kg, there is a slight slipping of the robot on the plane or cylinder surface, and the robot is difficult to adsorption stably. Under the same load, the robot has experienced adsorption failure on the spherical surface and has detached from the wall surface.

4.3. Motion testing

The prototype is placed in a variable curvature wall environment to test the adaptability of various motion modes. The test results are as follows.

Test A: As mentioned in Section 4.2, when the robot is adsorbed on the plane motion, the adsorption state is nearly the same as the robot without the compliant adjusting module and the pressure in the negative chamber is about 2.2 kpa. At this time, the robot can cross obstacles with a height of 2 mm, as shown in Fig. 13.

Test B: The sealing component is first compressed to maximum when the robot moves longitudinally on the cylindrical surface. The passive compliant mechanism compresses to varying degrees according to the change of wall curvature, ensuring effective contact between the track and the wall surface and realizing the robot’s adaptation to the wall surface. The robot is able to move across the groove on the

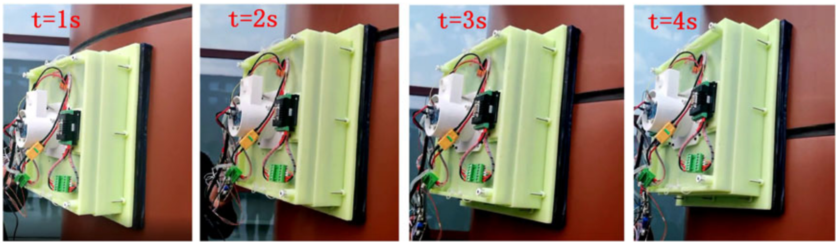

Figure 14. *Motion and groove crossing experiments of the robot on a cylinder wall.*

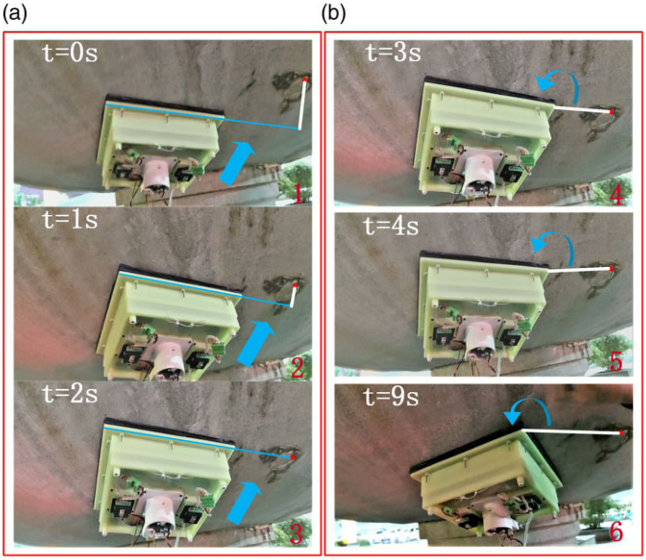

Figure 15. *(a) Linear motion experiments of the robot at the bottom of a spherical surface. (b) Steering motion experiments of the robot at the bottom of a spherical surface.*

cylindrical surface, and there is no significant slipping or adsorption failure occurring in the process, as shown in Fig. 14.

Test C: When the robot is adsorbed on the spherical surface, the sealing component wraps the wall surface to realize the sealing between the contact surfaces. The passive compliant mechanism will undergo a certain degree of compression deformation. As shown in Fig. 15(a), the robot moves forward in a straight line when the left and right tracks are given the same speed. The left and right tracks do not slip during the forward process, and the moving direction angle hardly changes.

Test D: In-situ turning test of the robot on a spherical surface. As shown in Fig. 15(b), during the steering process, as the angle increases, the track slips, and its maximum steering angle is related to the radius of the spherical surface.

Test E: The robot carries a 3.9 kg polishing tool and performs a simulated surface polishing test on the plane. In the operation process, the robot can freely realize acceleration and deceleration movement, which can meet the grinding needs while moving, as shown in Fig. 16.

4.4. Comparison of robot performance parameters

As shown in Table II, we selected five different locomotion model wall-climbing robots for performance parameter comparison. It can be found that the passive compliant wall-climbing robot is advantageous in the minimum adaptive radius of curvature than other robots. The wall-climbing robot in this study

Table II. *Performance parameter comparison.*

Program	**Locomotion**	**Speed (m/min)**	$\frac{1}{K}$ **(mm)**	**Load (N)**	**Weight (kg)**	$\frac{\textbf{Load}}{\textbf{Weight}}$
Our robot	Track	5	600	75	3	25
Traveling-wave-type [22]	Traveling wave	⊖*	900	48 (unit)**	1 (unit)	48
LARVA-II [23]	Wheel	⊜	≈ 3000	100	3.2	31.3
URARAKA IV [24]	Leg	⊖	⊖	⊖	3.3	⊝
Bi^2Copter [25]	Propeller	⊖	≈ 2000	23	2.5	9.2
LSBU [20]	Feet	0.6	⊜	180	20	9

*The data represented by ⊕ ⊖ ⊜ in the table are not provided. Through our evaluation, we use ⊕ to denote performance above our robot, ⊖ to denote performance below our robot, and ⊜ to denote performance similar to our robot.

**Ten units are required for the normal operation of the robot, and only the weight and load of one unit are provided in this paper.

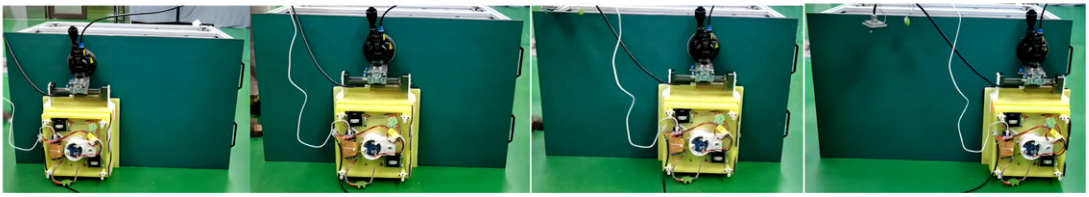

Figure 16. *The polishing and grinding operation experiments of the robot with the toolbox.*

with track structure has a good performance on locomotion, compared with other structures such as foot, propeller, and leg type.

In summary, it can be seen from the experimental and comparative results that the negative pressure adsorption passive compliant wall-climbing robot proposed in this paper can take into account the adsorption stability and variable curvature adaptability of the robot in a variable curvature environment. By using the force change of the compliant mechanism to passively adapt to the change of the wall surface, the robot can move stably on the variable curvature wall surface with any position and posture.

5. Conclusion and future work

In this paper, a novel wall-climbing robot with passive compliant mechanisms is designed. Compared with the typical wall-climbing robot, a passive compliant mechanism is introduced to passively adjust the position relationship between the sealing component and the mobile module, which helps the robot to be adsorbed on curved surfaces stably and move smoothly. The motion mechanism has been analyzed from stable adsorption conditions, parameter design process, and force analysis. A series of experiments have been carried out on load capability and curved surface adaptability based on the developed principle prototype. It has been demonstrated that the robot with passive compliant mechanisms has a good performance on adsorption stability and variable curvature adaptability.

In the future, our work is mainly toward autonomous adjustment of robot adsorption force on curved surfaces, mechanical design, and analysis of wall-climbing robots for intersection surfaces and other complex wall surfaces. At the same time, we would apply the developed robots to practical scenarios such as infrastructure inspection and maintenance.

Author contributions. All the authors participated in the conception, design, and writing of the article.

Financial support. This work was supported by the National Natural Science Foundation of China (52075529).

Competing interests. None.

Ethical approval. None.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S026357472300173X

References

[1] R. S. Bisht, P. M. Pathak and S. K. Panigrahi, “Design and development of a glass façade cleaning robot,” *Mech. Mach. Theory* **168**, 104585 (2022).
[2] H. Huang, D. Li, Z. Xue, X. L. Chen, S. Liu, J. Leng and Y. Wei, “Design and performance analysis of a tracked wall-climbing robot for ship inspection in shipbuilding,” *Ocean Eng.* **131**(1), 224–230 (2017).
[3] Z. Wang, K. Zhang, Y. Chen, Z. Luo and J. Zheng, “A real-time weld line detection for derusting wall-climbing robot using dual cameras,” *J. Manuf. Process.* **27**, 76–86 (2017).
[4] J. Liu, L. Xu, J. Xu, L. Liu, G. Cheng, S. Chen, H. Xu, J. Shi and X. Liang, “Analysis and optimization of the wall-climbing robot with an adsorption system and adhesive belts,” *Int. J. Adv. Robot. Syst.* **17**(3), 1729881420926409 (2020).
[5] A. Nishi, Y. Wakasugi and K. Watanabe, “Design of a robot capable of moving on a vertical wall,” *Adv. Robot.* **1**(1), 33–45 (1986).
[6] A. Nishi, “Development of wall-climbing robots,” *Comput. Electr. Eng.* **22**(2), 123–149 (1996).
[7] M. J. Spenko, G. C. Haynes, J. A. Saunders, M. R. Cutkosky, A. A. Rizzi, R. J. Full and D. E. Koditschek, “Biologically inspired climbing with a hexapedal robot,” *J. Field Robot.* **25**(4-5), 223–242 (2008).
[8] G. Caprari, A. Breitenmoser, W. Fischer, C. Hürzeler, F. Tâche, R. Siegwart, O. Nguyen, R. Moser, P. Schoeneich and F. Mondada, “Highly compact robots for inspection of power plants,” *J. Field Robot.* **29**(1), 47–68 (2012).
[9] Q. Zhou and X. Li, “Experimental investigation on climbing robot using rotation-flow adsorption unit,” *Robot. Auton. Syst.* **105**, 112–120 (2018).
[10] V. Boomeri and H. Tourajizadeh, “Design, modeling, and control of a new manipulating climbing robot through infrastructures using adaptive force control method,” *Robotica* **38**(11), 2039–2059 (2020).
[11] R. S. Bisht, P. M. Pathak and S. K. Panigrahi, “Modelling, simulation and experimental validation of wheel and arm locomotion based wall-climbing robot,” *Robotica* **41**(2), 433–469 (2023).
[12] J. Liu, L. Xu, S. Chen, H. Xu, G. Cheng and J. Xu, “Development of a bio-inspired wall-climbing robot composed of spine wheels, adhesive belts and eddy suction cup,” *Robotica* **39**(1), 3–22 (2021).
[13] Z. H. Liu, W. Cai, X. W. Fu, B. Yuan, H. Wang and Y. Song, “The failure analysis of a rolling sealed wall climbing robot,” *China Mech. Eng.* **33**(22), 2755–2763 (2022).
[14] D. Z. Jiang, J. Hu, H. Zhong, H. Wang, Y. Song and B. Yuan, “Analysis of safe adsorption conditions and motion characteristics of rolling sealed tracked wall-climbing robot,” *China Mech. Eng.* **32**(22), 2757–2764 (2021).
[15] C. Hillenbrand, D. Schmidt and K. Berns, “Cromsci - A Climbing Robot with Multiple Sucking Chambers for Inspection Task,” **In:** *Advances in Mobile Robotics* (2008) pp. 311–318.
[16] H. Li, X. Sun, Z. Chen, L. Zhang, H. Wang and X. Wu, “Design of a wheeled wall climbing robot based on the performance of bio-inspired dry adhesive material,” *Robotica* **40**(3), 611–624 (2022).
[17] C. Wang, J. Gu and Z. Li, “Switching Motion Control of the Climbing Robot for Aircraft Skin Inspection,” **In:** *2019 IEEE International Conference on Fuzzy Systems* (2019) pp. 1–6.
[18] Y. Guan, H. Zhu, W. Wu, X. Zhou, L. Jiang, C. Cai, L. Zhang and H. Zhang, “A modular biped wall-climbing robot with high mobility and manipulating function,” *IEEE/ASME Trans. Mechatron.* **18**(6), 1787–1798 (2012).
[19] M. Fujita, S. Ikeda, T. Fujimoto, T. Shimizu, S. Ikemoto and T. Miyamoto, “Development of universal vacuum gripper for wall-climbing robot,” *Adv. Robot.* **32**(6), 283–296 (2018).
[20] O. Madsen, J. Shang, T. Sattar, S. Chen and B. Bridge, “Design of a climbing robot for inspecting aircraft wings and fuselage,” *Ind. Robot.* **34**(6), 495–502 (2007).
[21] Y. Liu and T. W. Seo, “AnyClimb-II: Dry-adhesive linkage-type climbing robot for uneven vertical surfaces,” *Mech. Mach. Theory* **124**, 197–210 (2018).
[22] T. Amakawa, T. Yamaguchi, Y. Yamada and T. Nakamura, “Development of an Adhesion Unit for a Traveling-Wave-Type, Omnidirectional Wall-Climbing Robot in Airplane Body Inspection,” **In:** *proceedings of the 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)* (2017).
[23] I. M. Koo, T. D. Trong, Y. H. Lee, H. Moon, J. Koo, S. K. Park and H. R. Choi, “Development of wall climbing robot system by using impeller type adhesion merchanism,” *J. Intell. Robot. Syst. Theory Appl.* **72**(1), 57–72 (2013).
[24] M. Okino, K. Nagayama, K. Ito, T. Oomichi, S. Ashizawa and F. Matsuno, “URARAKA IV: Multi-Legged Robot with Suckers to Climb a Wall-Autonomous Climbing and Recovery from Miss-Adsorption,” **In:** *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO)* (2018).
[25] K. Kawasaki, Y. Motegi, M. Zhao, K. Okada and M. Inaba, “Dual Connected Bi-Copter with New Wall Trace Locomotion Feasibility That Can Fly at Arbitrary Tilt Angle,” **In:** *Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (2015).

Cite this article: Y. Song, Z. Yang, Y. Chang, H. Yuan and S. Lin (2024). “Design and analysis of a wall-climbing robot with passive compliant mechanisms to adapt variable curvatures walls”, Robotica **42**, 962–976. https://doi.org/10.1017/S026357472300173X