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REVIEW ARTICLE

# Design and Technical Development of Wall-Climbing Robots: A Review

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**Abstract**

Once working at heights is dangerous, it is a significant accident. These accidents brought substantial economic losses and caused a large number of casualties. Therefore, it is essential to use wall-climbing robots to replace manual work at heights. The design of the wall-climbing robot is inspired by the climbing action of insects or animals. An intelligent bionic robot device can carry special equipment to operate on the wall and perform some dangerous operations instead of firefighters or inspection personnel more efficiently. The scope of application is vast. This paper firstly summarizes the research progress of wall-climbing robots with three different moving methods: wheel-climbing, crawler-based, and leg-footed robots; summarizes the applications and breakthroughs of four adsorption technologies: negative pressure, magnetic force, bionic and electrostatic; discusses the application of motion control algorithms in wall-climbing robots. Secondly, the advantages and disadvantages of different migration modes and adsorption methods are pointed out. The distribution and advantages of the combined application of different migration modes and adsorption methods are analyzed. In addition, the future development trend of wall-climbing robots and the promoting effect of bionic technology development on wall-climbing robots are proposed. The content of this paper will provide helpful guidance for the research of wall-climbing robots.

**Keywords** Wall-climbing robot · Walking method · Adsorption technology · Motion control technology · Bionic

## 1 Introduction

Affected by industrial upgrading and the advancement of urbanization, the demand for vertical wall work in construction, transportation, petrochemical, nuclear energy, fire protection, and shipbuilding in various countries has dramatically increased, resulting in frequent falling accidents caused by high-altitude work. In recent years, thanks to the development of mechanical, hydraulic, electronic, computer, and bionic disciplines, many automatic mechanical devices that can move on the vertical wall and complete specific tasks have emerged. Making mechanical and electrical systems replace manual operations in dangerous and difficult conditions has become the development trend [1–6]. Inspired by the climbing of insects and animals such as geckos, spiders, beetles, and flies, the design and research of wall-climbing robots began. In the 1960s, Japan's A. NISHI et al. designed the first robot to move on a vertical wall, relatively small and clumsy. They completed the construction of the second-generation prototype in 1975 [7–9]. Since then, after more than 60 years of development, wall-climbing robots with different functions have been developed for specific purposes [10], which can complete dangerous work such as monitoring, inspection, maintenance, and engineering construction.It has been applied in many high-altitude work fields, such as nuclear leakage monitoring [11–14], wall thickness measurement [15, 16], weld inspection [17–20], ship rust removal [21–26], bridge maintenance [27–30], building cleaning [31–36], rescue and disaster relief [37, 38], investigation and rescue, etc. [39, 40]. Therefore, many scholars have proposed that we should study the critical technologies of wall-climbing robots to achieve stable motion while ensuring reliable adsorption and reducing or even getting rid of the dependence on operators.

The necessary functions of the wall-climbing robot include adsorption, movement, and operation, among which

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the operation belongs to the core function. Still, the operation unit is limited by the specific type of work and needs to provide suitable interfaces (including physical, electrical, control, etc.). Adsorption and movement are the basic functions and the premise to ensure the operation function. The core of developing a wall-climbing robot is to design reasonable adsorption and moving mechanisms and study critical technologies such as dynamic models, parameter matching, and walking control. Wall-climbing robots are an important part of intelligent bionic robots, which can make different decisions according to different wall surfaces and carry different equipment for efficient special operations. Therefore, the research on wall-climbing robots has essential research significance and application value for improving the intelligence level of industries and fields, improving production efficiency, and reducing manual operation risks.

The rest of this paper is organized as follows. In Sect. 2, the wall-climbing robots with wheeled, crawler, and legged movement mechanisms are introduced, respectively. In Sect. 3, the development of four leading adsorption technologies of negative pressure, magnetic force, bionic and electrostatic for wall-climbing robots is summarized, including the application and development of bionic mechanisms and bionic materials in wall-climbing robots. In Sect. 4, motion control techniques for wall-climbing robots are discussed. In addition, in Sect. 5, through data statistics and comparative analysis, the advantages and disadvantages of different moving methods and adsorption methods are pointed out. The benefits of different moving and adsorption methods combined are analyzed. In Sect. 6, the future research directions and trends of wall-climbing robots are discussed and the promotion of the development of bionic technology on the research of wall-climbing robots. Finally, conclusions are given in Sect. 7.

## 2 Walking Method of Wall-Climbing Robot

Because of different working environments and work requirements, the walking devices selected when designing wall-climbing robots will be different. So far, the main motion mechanisms of most wall-climbing robots are wheeled, crawler and legged.

### 2.1 Wheeled Wall Climbing Robot

The wall-climbing robot of the wheeled walking device has the characteristics of flexible turning and fast-moving speed, so the wall-climbing robot of the wheeled walking mechanism is more common, as shown in Fig. 1.

Wagner designed non-contact adsorption wheeled wall climbing robot based on Bernoulli's principle [41]. Journee improved its structure, and the improved robot has improved carrying capacity and moving speed [42]. Wu et al. developed a wall-climbing robot for reconnaissance purposes, including two driving wheels and a guide wheel, which can move quickly and adapt to almost all types of vertical wall surfaces in urban environments [43]. To solve the problem

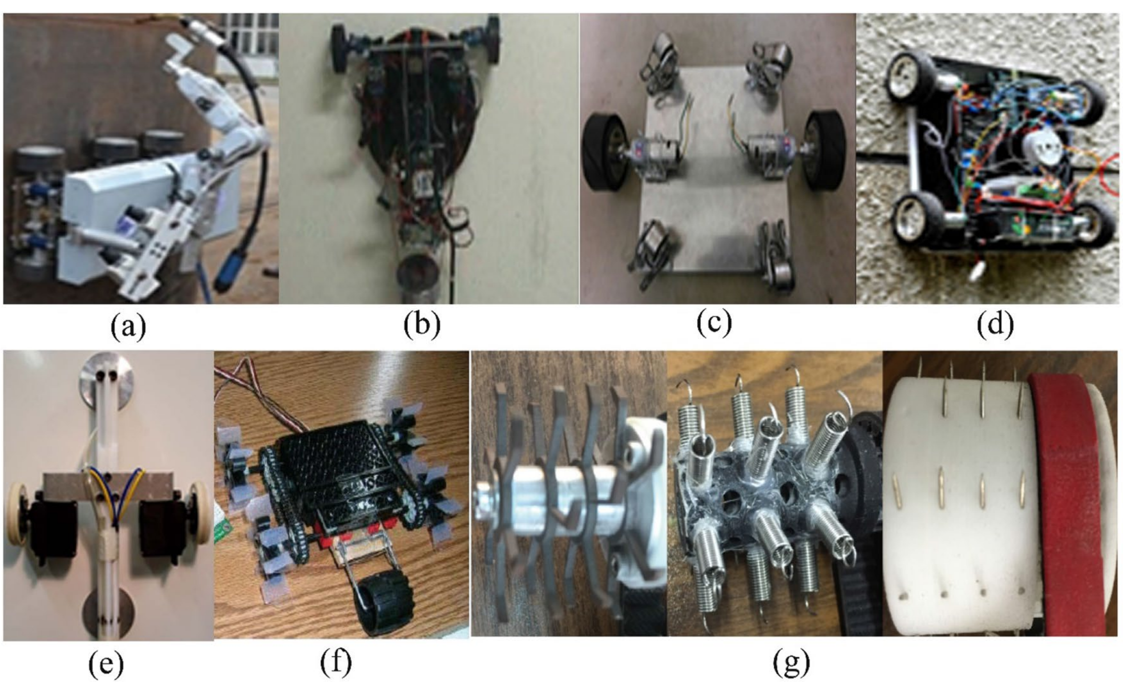


**Fig. 1** Wheeled wall-climbing robot. **a** Ref. [19], **b** Ref. [45], **c** Ref. [46], **d** Ref. [47], **e** Ref. [53], **f** Ref. [54], **g** Ref. [55]

of wheeled robots' poor ability to overcome obstacles, the Alicia3 robot of the University of Catania in Italy connects three Alicia II modules in series through two connecting rods. The three modules can be peeled off the wall and repositioned, gradually crossing the obstacles. The disadvantage of this method is that the moving speed is low, and the control system is complicated [44]. The LARVA wheeled wall-climbing robot of Sungkyunkwan University in South Korea is equipped with two driving wheels with a suspension system to prevent the robot's body wall from detaching [45]. Hidenori Ishihara researched a wall-climbing robot with passive magnetic wheels. The robot consists of two driving wheels and four passive wheels with magnetic tires. The passive wheel comprises a suspension mechanism, a caster mechanism and a magnetic tire [46]. The kinematic mechanism of the wheeled wall-climbing robot designed by Zhou and Xin includes four independent driving wheels, which are steered by the rotation speed difference of the left and right wheels of the robot [47]. Wu et al. designed a six-wheeled wall-climbing robot. To pass obstacles, the suction cup and wheel unit can be moved longitudinally by the lifting mechanism [19]. Zhang et al. proposed a compact omnidirectional permanent magnet wheel type wall-climbing micro-robot. The omnidirectional wall-climbing mechanism is realized by a set of steering gear and three standard permanent magnet wheels [48]. Xu et al. designed a magnetic wheel with optimized adhesion ability and optimized the size of the wheel to meet the requirements of a hull wall-climbing robot for payload and surface adaptability [49]. Howlader and Sattar described the detailed design of a new robot climbing concrete structure attachment mechanism. The walking mechanism of the machine is composed of 4 wheels with no adsorption effect [50]. Liang introduced a wall-climbing robot that uses the reverse thrust of the propeller as the adsorption force to test the motion performance and adaptability of the robot under different ground/wall environments to verify the stability and feasibility of the robot [51]. Song et al. developed a wheeled wall-climbing robot that uses a permanent magnet adhesion system to climb on large steel surfaces. To avoid wheel traction and slippage, the use of pneumatic rubber tires has been increased while maintaining the air gap required by the magnet system [52].

There are three main types of wall-climbing robots with wheeled walking mechanisms in the most current research. The first is a rubber-wheel walking mechanism. The manufacturing of rubber wheels is relatively simple and easy to process, and the friction coefficient of rubber materials is high. It is light, which reduces the weight of wall-climbing robots and is widely used in robots [56–59]. The second type is a magnetic wheel made of metal materials. The magnetic wheel itself is cross-weighted and has a relatively simple structure. It is primarily used in magnetically attracted wall-climbing machines [60–63]. Wall-climbing robots with ratchet mechanisms are relatively rare. There are two main types of ratchets used in wall-climbing robots. One is a ratchet with a bionic viscous adsorbent material. The bionic adsorption materials used are diverse, have good adhesion properties, and improve the climbing ability [64–67]. The other is a ratchet mechanism with thorns, which is designed with reference to the claw thorns of insects or animals [55, 68, 69].

The wheeled wall-climbing robot mainly moves with two or more wheels. The number of wheels of the currently designed wall-climbing robot can be divided into two, three, four, and six wheels. Among them, the two-wheeled wall-climbing robot is not stable enough when braking and moving at low speed. The three-wheeled wall-climbing robot is divided into two types: front-drive and rear-drive, with steady travel and flexible steering. The wall-climbing robot with a four-wheel device has a more robust bearing capacity and sufficient driving force than the three-wheel structure under the condition of ensuring steering. The six-wheel walking mechanism is mostly used in wall-climbing robots with magnetic adsorption. Some wheeled wall-climbing robots have designed obstacle-surmounting mechanisms to improve walking stability, and this walking mechanism is often multi-wheeled.

## 2.2 Crawler Type Wall Climbing Robot

Figure 2 shows the wall-climbing robot with a crawler walking mechanism. The wall-climbing robot designed by Ritsumeikan University in Japan installs passive suction cups on the crawler. It does not need additional energy to

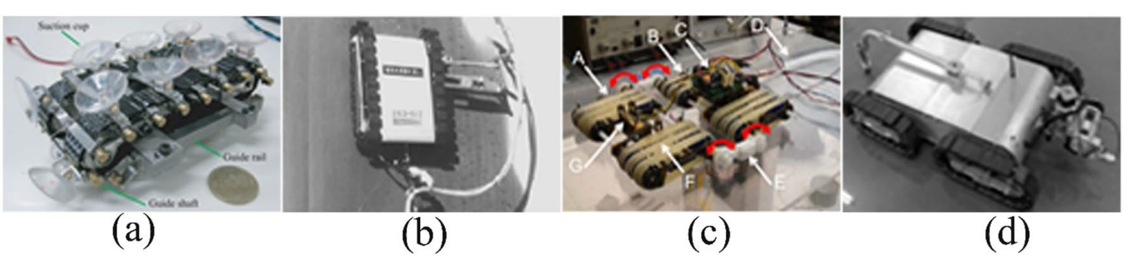


**Fig. 2** Crawler-type wall-climbing robot. **a** Ref. [70], **c** Ref. [74], **b** Ref. [80], **d** Ref. [83]

maintain adhesion and climb on the wall with lower energy consumption [70]. The crawler wall-climbing robot developed by Seoul University in South Korea has a suction cup installed on each crawler plate. A mechanical valve is used to control the suction cup to achieve continuous movement of the crawler on the wall [71, 72]. The oil tank detection synchronous toothed belt magnetic adsorption crawler wall-climbing robot developed by Xu and Ma installs permanent magnets on the crawler. The permanent magnets on the crawler are sequentially adsorbed and detached from the wall surface as the crawler rotates, realizing the movement of the wall-climbing robot on the surface of the magnetic metal wall [73]. Shen of Dalhousie University and others introduced a wall-climbing robot that directly uses permanent magnets to make track shoes [74]. Carnegie Mellon University in the United States has developed an electromagnetic adsorption crawler wall-climbing robot, which is equipped with redundant crawlers at the front and rear of the robot, which can assist the robot in crossing obstacles [75]. Shen et al. proposed an oil tank inspection wall-climbing robot based on a permanent magnet adhesion mechanism. The robot uses a crawler motion mechanism. When the robot moves, a certain number of units are in good contact with the surface so that the robot can reliably stay on the surface [76]. Tovarnov and Bykov established a mathematical model of a mobile robot with a crawler motion mechanism moving on a vertical surface and studied the robot's motion stability and the dependence of the drive motor capacity on the moving speed [77]. Wang et al. developed a crawler-driven wall-climbing robot that can pass simple obstacles [78]. Fukui et al. proposed a crawler-mounted mobile robot mounted on the ceiling. It is highly mobile and can freely choose and adjust its route under the ceiling [79].

Reconfigurable and modular crawler wall-climbing robots have more movement freedom and better climbing ability. South Korea's Lingnan University proposed a modular crawler-type wall-climbing robot, which consists of two sets of double-track devices, uses a direct current motor to drive differential steering, and can well conform to the wall [80]. Liu et al. proposed a crawler wall-climbing robot with bionic vertebral feet. The robot's trajectory consists of a dozen vertebral feet attached to rough surfaces. Compared with footed crawling robots, crawler crawling robots have more spines, and the adhesion performance can be improved [81]. Park et al. designed a wall-climbing robot consisting of three identical modules. Each module is an independently tracked wall-climbing robot. The experimental results show that the robot can transform between various vertical walls [82].

Fault detection has always been an enormous challenge. Zhang et al. designed a wall-climbing robot with a four-track structure for non-destructive testing of metal welds [83]. There are more and more applications of crawler wall-climbing robots with detection capabilities, such as ship rust removal, ship inspection, metal tank inspection, etc. [84–86].

The crawler-type wall-climbing robot realizes basic movement by driving the crawler by the driving wheels on both sides. The differential steering of the tracks on both sides can change the turning radius, enabling the robot to turn in place on the wall, making it more flexible and maneuverable when turning. When the crawler-type wall-climbing robot works on the wall surface, the contact area between the crawler and the wall surface is large, and the friction force is also significant, which ensures that the movement and rotation of the robot on the wall surface are more stable. The wheeled wall-climbing robot can only go around when the wall surface is uneven, while the crawler-type wall-climbing robot can pass directly.

### 2.3 Leg-Foot Wall-Climbing Robot

There are often various defects and uneven obstacles on the complex wall surface. The continuous path that can stably support the robot's movement is limited. The wall-climbing robot with poor ability to overcome the barriers will be difficult to move to the target position directly. The driving path domain of the robot from the starting point to the target point consists of several disconnected curves. This situation means that wheeled and tracked robots are no longer suitable for this terrain. When the legged robot moves, it only needs discrete points to touch the ground, which is more adaptable, and the legged robot has minor damage to the environment. As shown in Fig. 3, it is a wall-climbing robot with a legged walking mechanism.

Inspired by nature, such as insects and geckos that can climb on walls and ceilings [91], the leg-foot structure is one of the commonly used mobile mechanisms for wall-climbing robots [10]. The Robin robot designed by Vanderbilt University connects two vacuum suction devices through a 4-degree-of-freedom hinge mechanism to walk on the wall and move from the horizontal ground to the vertical wall [92]. Wichita State University designed a two-legged mobile robot that can move between different planes and established the Jacobian matrix to analyze the kinematics and safety of the robot [93]. Tummala et al. of Michigan State University and others introduced two under-actuated mechanical kinematics designs of miniature wall-climbing robots. This design contains fewer actuators and reduces the robot's weight, which helps reduce the size and increase the movement speed, but the actual speed is limited by the delay of the suction cup control [94]. The ROMA robot of the Carlos III University of Madrid composes two grippers into an 8-DOF motion mechanism driven by an AC servo motor through a harmonic drive reducer, which can realize three-dimensional motion on complex structural surfaces[95]. The

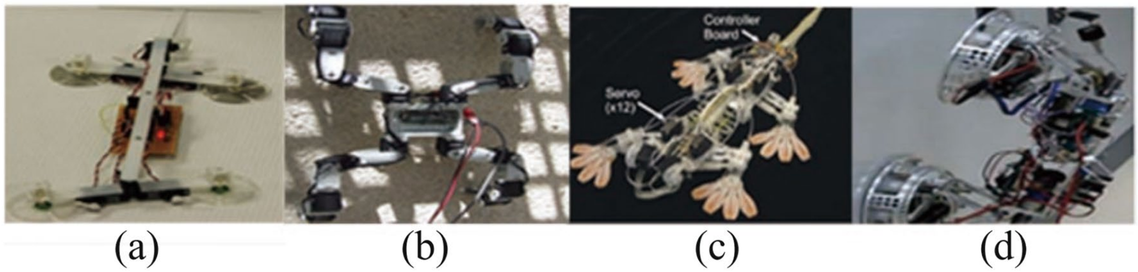


**Fig. 3** Leg-foot wall-climbing robot. **a** Ref.[87], **b** Ref. [88], **c** Ref. [89], **d** Ref. [90]

Stickybot robot developed by Stanford University has a similar compliant control strategy, which allows the robot's four legs to maintain a sizeable contact area with the wall so that the adhesion force can support the robot on smooth glass ceramic tiles and plastic plates[89]. The Geckobot robot from Carnegie Mellon University has a kinematic structure similar to a gecko. In addition, an active tail wing is added to improve the steering flexibility and stability of the robot. The advantage of this legged robot is that it can better adapt to irregular surfaces [87]. The CLIBO robot from Ben-Gurion University in Israel has four legs, each with 4 degrees of freedom. Additionally, each leg is attached with a specially designed claw that mimics the way cats use their claws to climb trees. Experiments have demonstrated the reliability of this structure[88]. The RVC robot of the University of Technology Sydney, Australia, is composed of walking modules. Each module has a pair of legged walking structures with 3 degrees of freedom, and the modules are connected by a joint with 2 degrees of freedom. The robot can be composed of at least two modules to form a quadruped robot, and the load capacity and safety can be improved by expanding more modules [96]. Illinois Institute of Technology's hexapod robot RiSE is the first footed robot to move up to 4 cm/s on various vertical building surfaces on the ground. Cockroaches inspired the design of the robot. Each leg of the robot is composed of independent modules with two degrees of freedom. This modular design is low cost, lightweight and flexible in configuration. The experimental results prove that the robot has a reliable long-distance climbing ability [97]. Li et al. proposed a new type of combined hexapod wall-climbing robot for use in the field of anti-terrorism. With the help of the passive joint of the ankle joint and the silent vacuum generator, it can move quickly and quietly [98]. Wang et al. proposed a novel flexible pneumatic wall-climbing robot consisting of a flexible pneumatic ball joint and six suction cups. It has the characteristics of low cost, lightweight, simple structure, and good flexibility [99]. He et al. analyzed the degrees of freedom of a hexapod wall-climbing robot using the spiral theory and proposed a new simple Jacobian matrix to analyze the singularity of the robot.[100]. Albee et al. presented a wall-climbing planner simulation using a quadruped wall-climbing robot as an example and successfully recognized, navigated and climbed any vertical wall on a hardware demonstration test bench [101].

The gait planning of the legged wall-climbing robot is related to its locomotion ability. Hong designed a small multi-joint wall-climbing robot based on vibrating suction cups and performed gait planning for three typical walking actions: straight walking, turning, and face-to-face transfer. The experimental results verify the feasibility of the robot. It can walk from the ground to the wall, crawl and rotate on the wall, and then walk to the ceiling [90]. Tokyo Institute of Technology tested the mobility of the quadruped structure based on the quadruped wall-climbing robot NINJA-I [102] and studied the gait problem of the robot on vertical and flat walls [103]. Tim Bretl of Stanford University et al. proposed a new four-arm robot LEMUR IIb at the end of the actuator is equipped with pins wrapped in high friction rubber, equipped with onboard batteries, CPU, and sensors. A safe single-step climbing motion planning algorithm is proposed to enable LEMUR IIb to climb indoor vertical surfaces [104]. Gao et al. designed the foot motion and body pitching strategy of the hexapod wall-climbing robot (WelCH) in detail. Simulation and field experiments of the robot WelCH from horizontal ground to vertical walls verify the effectiveness of this strategy [105]. Stanford University's climbing robot SpinybotII is similar to some insects and spiders. Each set of mechanisms is connected with three legs. The two sets of mechanisms alternately climb along the wall in a triangular gait and are equipped with a tail structure to reduce pitching. This robot can carry a payload equal to its weight and remain attached without consuming power [106].

Hydraulic devices or motors drive the legged wall-climbing robot at the mechanical joints to perform movements similar to the action of biological limbs to achieve flexible steering. The legs of the legged wall-climbing robot have multiple degrees of freedom, which significantly enhances the flexibility of movement, which greatly improves its ability to overcome obstacles. However, this kind of foot-type kinematic system is very complicated in design, production, installation, maintenance, difficult to control, and poor stability. Legged walking mechanisms can be divided into two categories according to their different ways of maintaining balance when walking: statically stable multi-legged mechanisms and dynamically stable multi-legged mechanisms.

### 2.4 Multi-Structure Walking Device

The design of the wall-climbing robot needs to be adjusted according to the specific requirements of the working environment. Figure 4 shows the wall-climbing robot with hybrid mobile mode. Liu et al. proposed a new type of wall-climbing robot with multiple attachment methods for walls with different roughness. The mechanical model of a bionic ratchet is used for uneven surfaces to grasp the surface through its multiple ratchets, which are adhered to by polyurethane material. The track formed on the surface of the industrial timing belt can move on a smooth surface, and the suction device with a flexible skirt can prevent the robot from overturning [107, 108]. Dong et al. proposed a wall-climbing robot with a biped wheeled hybrid mobile mechanism for anti-hijacking tasks, combining wheeled and footed robots' advantages, enabling the robot to move quickly and easily across obstacles [39]. Kim et al. develops a multi-body mobile robot with wall-climbing and wall-to-wall conversion capabilities. The robot consists of three connecting bodies, two connecting rods, and ten crawler wheels driven by nine motors. Six vacuum suction cups are installed on each track wheel, and a suction cup is attached to the second body for the steering movement of the entire robot. Experiments have verified the robot's performance in the case of vertical wall climbing and 90° wall transition—ability [109]. Lee et al. of Central University in South Korea and others proposed a flexible wall-climbing robot with wall transition ability. The robot consists of three modules with magnetic pedals. These modules are connected by compliant joints and conform to the shape of the wall through active torque control [110]. To increase the contact area between the wheeled wall-climbing robot and the wall, Kim et al. use four triangular tracks instead of the wheeled walking mechanism [33, 111].

## 3 Adsorption Method of Wall-Climbing Robot

The research and application of wall-climbing robots have broad engineering application prospects. The design of the adsorption device is the core technology for the wall mobile robot to complete the wall movement. At present, the mainstream adsorption technologies include negative pressure adsorption, magnetic adsorption, bionic adsorption, and electrostatic adsorption.

### 3.1 Negative Pressure Adsorption

Negative pressure is when the pressure in a specific area is lower than atmospheric pressure. The relatively high-pressure atmosphere flows to the negative pressure area, generating a particular force. As shown in Fig. 5, the negative pressure adsorption principle of the wall-climbing robot is also similar. The negative pressure adsorption method mainly relies on the pressure difference inside and outside the suction cup to squeeze the robot against the wall through atmospheric pressure. Most negative pressure adsorption wall climbing robots use negative pressure generating devices such as high-speed fans, or vacuum pumps to discharge the air in the suction cups to form negative pressure or partial vacuum. Therefore, vacuum adsorption is also a way of negative pressure adsorption.

The first wall-climbing robot born in 1966 used the principle of low pressure on the intake side of the electric fan to achieve the adsorption function [7]. In 1990, Zhao et al. developed a negative-pressure wall-climbing robot for welding seam inspection of nuclear waste storage tanks. Since then, a single-suction wall-climbing robot CLR for clear walls of tall buildings was born [114]. Hong et al. developed a new vibrating suction cup based on the working principle

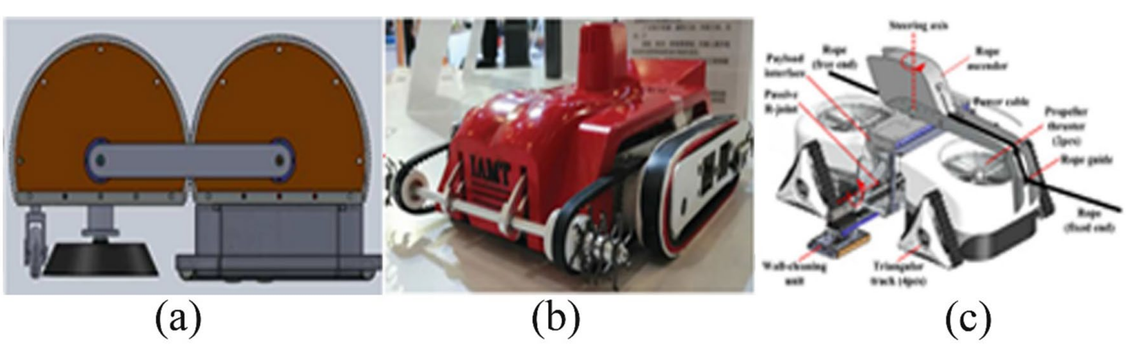


**Fig. 4** Hybrid wall-climbing robot with multiple walking modes. **a** Ref. [39], **b** Ref. [107], **c** Ref. [111]

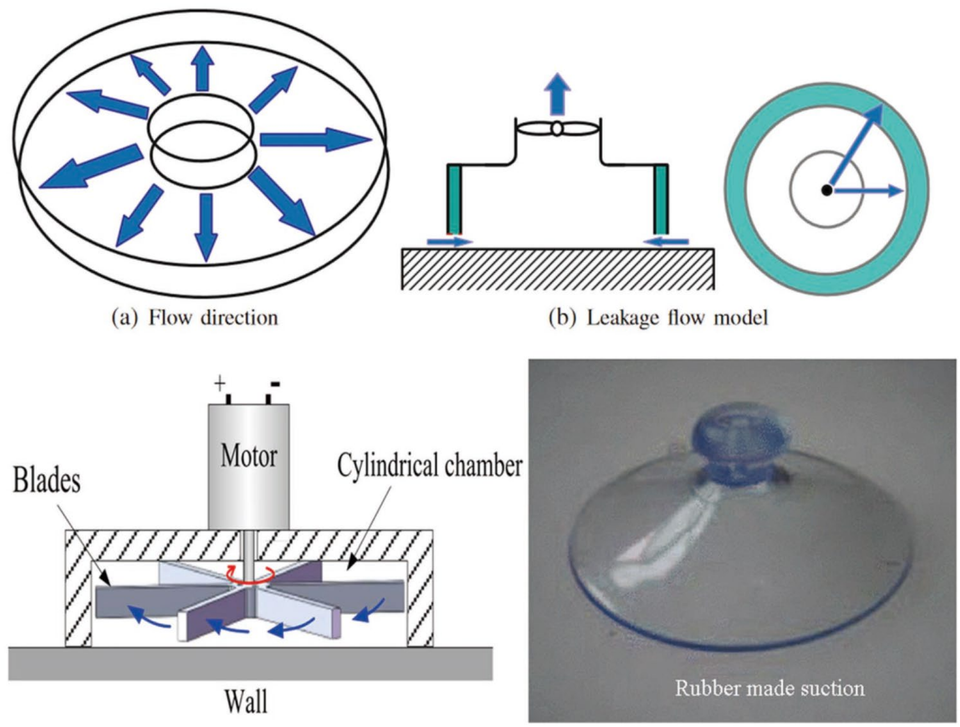


**Fig. 5** Negative pressure adsorption method [57, 112, 113]

of a vacuum pump [90]. The shape of the suction cup is optimized, and the square sealing cavity significantly increases the suction cup area, enabling the robot to cross obstacles with a height of 15 mm [47]. Song et al. designed an adsorption system consisting of an impeller and two layers of seals. The adsorption device can provide enough adhesion during the experimental test to support the robot adsorbed on vertical walls and ceilings [45]. Chen et al. proposed a new type of negative pressure technology based on the principle of vibration absorption. Based on this, they developed a prototype of a gecko climbing robot and designed the vibration absorption module as the foot of the wall-climbing robot [115]. Li and Dong proposed a suction cup with motorized blades, which solved the traditional vacuum leakage problem and adsorbed on objects with rough and uneven surfaces [116]. Liu et al. introduced a new wall-climbing robot that can detect smooth wall surfaces. The robot is composed of a vacuum adsorption system and an adhesive tape, which is flexible and manipulated effectively [108]. Shi and Li studied a zero-pressure-difference vacuum adsorption method. The experimental prototype verified that this method could effectively prevent air leakage in the edge area of the negative pressure chamber [117]. Chashchukhin et al. studied the positioning problem of wall-climbing robots adsorbed by negative pressure [59].

The stability of a single suction cup is poor, and there is a risk of adsorption failure. To improve safety, some wall-climbing robots have installed multiple vacuum suction cups on the track to increase the suction force [72, 118, 119]. Adopting multiple suction cups can improve the load-bearing capacity and wall adaptability of the wall-climbing robot. However, it will make the structure more complicated, making it difficult to control and turn. Zhao et al. proposed a wall-climbing robot using a suction unit, which uses eddy currents to generate suction. Unlike the traditional contact-based suction unit, the suction unit can maintain suction without contact with the wall surface [120]. Chen uses a rotating flow suction unit to attach the wall-climbing robot to the wall in a non-contact manner so that it can climb up rough walls and overcome obstacles. In the rotating flow suction unit, the air driven by the blades rotates at high speed in the chamber, thereby generating and maintaining negative pressure [113].

The improvement of the negative pressure adsorption device can increase the adsorption force. Therefore, the analysis, research, and optimization of the adsorption device and the negative pressure driving method are necessary [121–123]. The maneuverability of the negative pressure adsorption robot largely depends on the air pressure in the negative pressure chamber. Use the air pressure sensor to monitor the pressure value in the negative pressure chamber and keep the pressure in the negative pressure chamber constant, which can improve the smoothness of the wall-climbing robot when moving [124]. The performance of the negative pressure adsorption device determines the stability and safety of the wall-climbing robot. More and more researchers have used numerical calculations and fluid dynamics simulation to carry out the necessary analysis, improvement, and optimization of the adsorption device [58, 125, 126]. Koo et al. carried out static and aerodynamic modeling of the negative pressure mechanism. They analyzed the negative pressure mechanism, air leakage, and internal flow, which provided a basis for design and control [127]. Bo et al. proposed a theoretical analysis method for the design of wall-climbing robots. Based on the effective utilization of the aerodynamic attraction of a centrifugal blower, an optimization mechanism was given [128]. Shujah et al. established a centrifugal fan model, calculated the flow rate of the centrifugal fan according to the required negative pressure, and determined the size of the negative pressure system [129].

The critical core of the negative pressure adsorption method is the need to generate a pressure difference. A negative pressure area is generated through the fan's rotation in the adsorption device, and the pressure difference between the inside and outside of the negative pressure chamber can be formed. In addition, according to the aerodynamic theory, a pressure difference is formed above and below the propeller disc through the propeller's rotation, and the generated thrust can make the wall-climbing robot stably adsorb on the wall [130, 131]. Figure 6 shows a wall-climbing robot with propeller thrust adsorption. Jae-Uk Shin designed a quadrotor wall-climbing robot. Using the thrust of the four rotors can achieve the function of sticking to a vertical wall and flying. The wheeled walking device can ensure that the robot moves on the wall. It can return to its original position even if it is accidentally detached from the wall while climbing the wall. Experimental results show that it has high maneuverability and safety [132]. Kawasaki et al. devised a mechanism to connect two twin-rotor modules, combining two of the four propellers. This structure effectively utilizes the thrust generated by the propeller and realizes the function of continuous rotation of the tilt angle and the flight function of maintaining any tilt angle. Experimental results demonstrate that it can be moved on curved walls by adsorption [133]. Peng Liang introduced a wall-climbing robot with two propellers with symmetrical structures. The reverse thrust component of the propeller and the driving force of the front wheels enable the robot to perform wall movement. Adaptability tests verify the stability and feasibility of the robot under different ground/wall environments [51]. Alkalla et al. designed a wall-climbing robot with two coaxial upturning propeller structures based on the

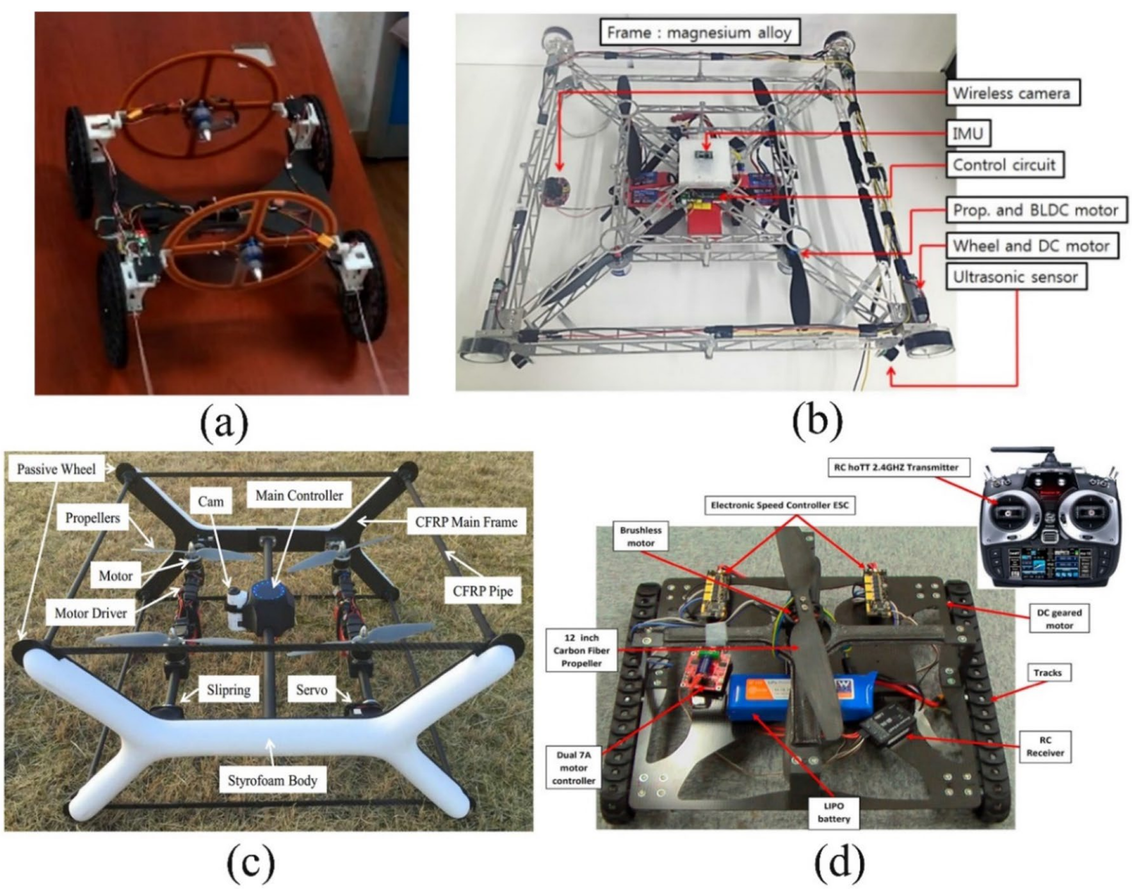


**Fig. 6** Propeller thrust adsorption. **a** Ref. [51], **b** Ref. [132], **c** Ref. [133], **d** Ref. [134, 135]

propeller-based aviation system. The robot can utilize propeller thrust and wheel torque to provide driving force [134, 135].

The negative pressure adsorption method mainly relies on the pressure difference so that the wall-climbing robot can be tightly attached to the wall surface under atmospheric pressure. The pressure difference can be generated by high-speed centrifugal fans, vacuum pumps, propellers, rotors, and other devices. Different methods are suitable for different environments, have broad applications, and maintain good adsorption capacity.

### 3.2 Magnetic Adhesion

The adsorption method of magnetic adsorption wall-climbing robot can be divided into electromagnetic adsorption and permanent magnet adsorption. Electromagnetic adsorption is based on the principle of electromagnetic. The magnetic force is generated by energizing the coil to adsorb on the surface of magnetic metal. The magnetism is easy to control, but the safety is poor [74]. The wall-climbing robot with permanent magnet adsorption is based on the magnetic force of the permanent magnet for adsorption. The adsorption capacity is strong and stable. The adsorption force can be adjusted according to the distance between the magnet and the wall. The disadvantage is that the robot can be removed by isolation at the end of the work. The principle and application of magnetic attraction are shown in Fig. 7. In recent years, many scholars have developed many wall-climbing robots for welding, inspection, and maintenance of large structural parts based on the principle of magnetic adsorption [50, 86, 136, 137].

Due to the reliable adsorption and simple structure, most of the current magnetic adsorption wall-climbing robots use permanent magnet adsorption. One common structure is installing permanent magnets on the ends of the robot legs [139–142], which can overcome gaps and obstacles while stably adhering to the surface. Akinfiev et al. analyzed and calculated the robot's stability under the conditions of turning and sliding [143]. Cui et al. designed a permanent magnet adsorption support device to achieve reliable adsorption and flexible movement on complex curved surfaces [144]. Since the magnetism of permanent magnets cannot be changed, servo motors, magnetic switch devices, and tilt pedal mechanisms are generally used to adjust the contact gap to control the adsorption force. Magnetic wheels have the advantages of continuous movement and fast speed. To improve the mobility and flexibility of the magnetic adsorption robot, some scholars have proposed to use omni wheels [145, 146] as a mobile device, which can move and rotate in any direction on the wall. Fischer et al. proposed a lightweight magnetic wheel-type wall-climbing robot for inspecting the inner surface of the fuel tank of a marine vessel [147]. Schoeneich proposed a magnetic wheel-type miniature wall-climbing robot similar to a training structure, which can move within a 25 mm diameter iron pipe

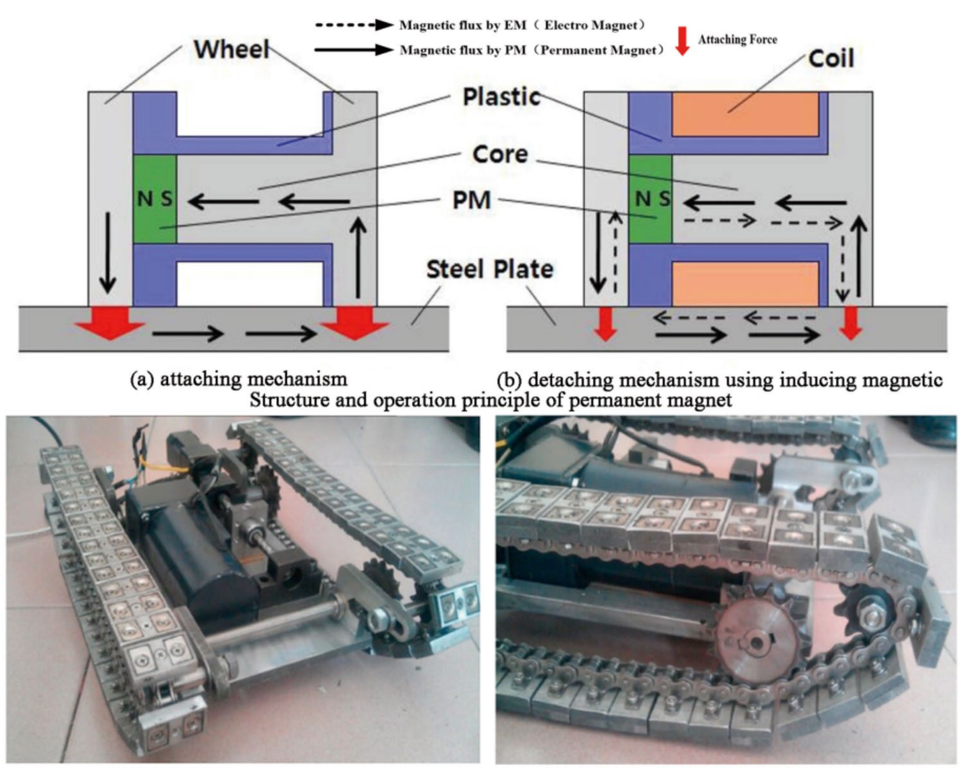


**Fig. 7** Magnetic adsorption method[85, 138]

and transmit images through a cable, which can be used for pipeline inspection of power plant boilers [148]. Although the magnetic wheel is flexible in movement, its load capacity is poor due to its small contact area with the wall. Another common magnetic adsorption method is to install permanent magnets on the track shoe, or the track shoe itself is magnetic. Each track shoe is adsorbed and separated from the wall in turn during the movement, which has stable adsorption performance and strong obstacle crossing [73, 74, 110, 149]. The disadvantage is that the mass is usually large, the movement is not flexible enough, and it is prone to difficult steering.

The mobility research of the magnetic adsorption wall-climbing robot is one of the key technologies. Yan et al. proposed a multi-directional magnetized permanent magnet adsorption device for wall-climbing robots. The new permanent magnet adsorption device contains multiple permanent magnets that are closely arranged and magnetized in different directions. Under the same quality conditions, the adsorption device can significantly improve the adsorption capacity [150]. Chen et al. designed a new permanent magnet attachment system based on a linear Halbach array, established the adhesion mechanism, measured the maximum and minimum adhesion force, and compared with the numerical simulation results, the results are in good agreement [151]. The technical bottleneck of the magnetic adsorption wall-climbing robot is that the magnetic force is both the adsorption force and the motion resistance—the greater the magnetic attraction force, the greater the motion resistance of the robot. To solve this problem, Huang et al. proposed a unique wall-climbing robot based on electromagnetic adsorption. The electromagnets fixed in the synchronous belt enter or leave the work sequentially to achieve the unity of adsorption and migration [152]. Chen et al. can change the magnetic field in the air gap by rotating the central axis of the adhesion mechanism to change the magnetic adhesion force, which is convenient for the robot to adhere to and detach from the wall [153]. Kim et al. uses permanent magnets to enhance the adhesion during the adhesion process and uses electromagnets to weaken the magnetic field of the permanent magnets, reduce the adhesion, and make the wheels easier to detach from the steel plate [138]. Fan et al. adopts a new permanent magnet adsorption mechanism with an electromagnetic method and internal force compensation principle. By configuring permanent magnets, electromagnets, and nonlinear springs, it can achieve a reliable adsorption function with the smallest separation force. Experimental results show that it has fast and controllable adsorption–desorption capacity and has lower power [154].

The adsorption method of the permanent magnet or electromagnetic is more stable in terms of adsorption force, and the safety is more reliable. Therefore, the magnetic adsorption wall-climbing robot can carry more equipment for operation. However, the working environment of the magnetic adsorption wall-climbing robot is limited to the metal wall surface with magnetic permeability.

### 3.3 Bionic Adhesion

Bionics and biorobots are a flourishing field of modern scientific research. With the development of this technology, wall-climbing robots have a wide range of practical application potential. The biomimetic adsorption structure is mainly based on imitating the principle of adhesion of biological feet in nature, as shown in Fig. 8. It mainly includes the attachment method based on claws and thorns [69, 155] or the adhesion method that generates van der Waals force between the microstructure and the contact object [156, 157]. These methods are suitable for rough surfaces to provide a graspable structure or sufficient contact points [158].

In 1965, the biologist Rodolfo Ruibal put the gecko's feet under an electron microscope and discovered that the ends of the bristles that looked like small hooks were split. Each bristle is divided into 100–1000 finer hairs. These hairs significantly increase the area of the gecko's soles, especially when the gecko climbs on the surface of those rough objects; these fluffs can fill the small hollow[159]. In this way, the villi on the bristles of the gecko's toes have a large contact area with the object's surface, and there is an attractive force between molecules and molecules. This force is called van der Waals force, although the van der Waals forces between a single pair of molecules are tiny. However, if the number of interacting molecules is enormous, the superposition of these tiny forces will be considerable [160]. Inspired by geckos, many scholars have studied adsorption materials to simulate the tendon tissue and skin of gecko's toes and simulated the adsorption process of geckos by the van der Waals forces generated by close contact with objects on the micrometer and sub-micrometer scales. Based on the crawling gaits of geckos and lizards, Wang designed a hook-and-claw quadruped wall-climbing robot. The robot is driven by five servo motors, four of which are used to control the grasping motion of the hooks and feet, and one is used to control the twisting of the waist. Experiments show that the robot's crawling efficiency on the wall is significantly improved [161]. Chen et al. proposed a prototype of a gecko wall-climbing robot based on a vibrating suction mechanism. The tripod gait of the gecko is also considered in the robot's motion planning. Combining the unique characteristics of the vibrating suction mechanism and the gecko's tripod gait, it has obtained the advantages of stable motion, a specific bearing capacity, anti-overturning ability, and good suction to the wall [115]. Dharmawan introduced the design, modelling, and force analysis of a wheel-legged robot that uses double-layer dry adhesive to climb walls. The double-layer synthetic gecko adhesive includes a layer of micro-pillar

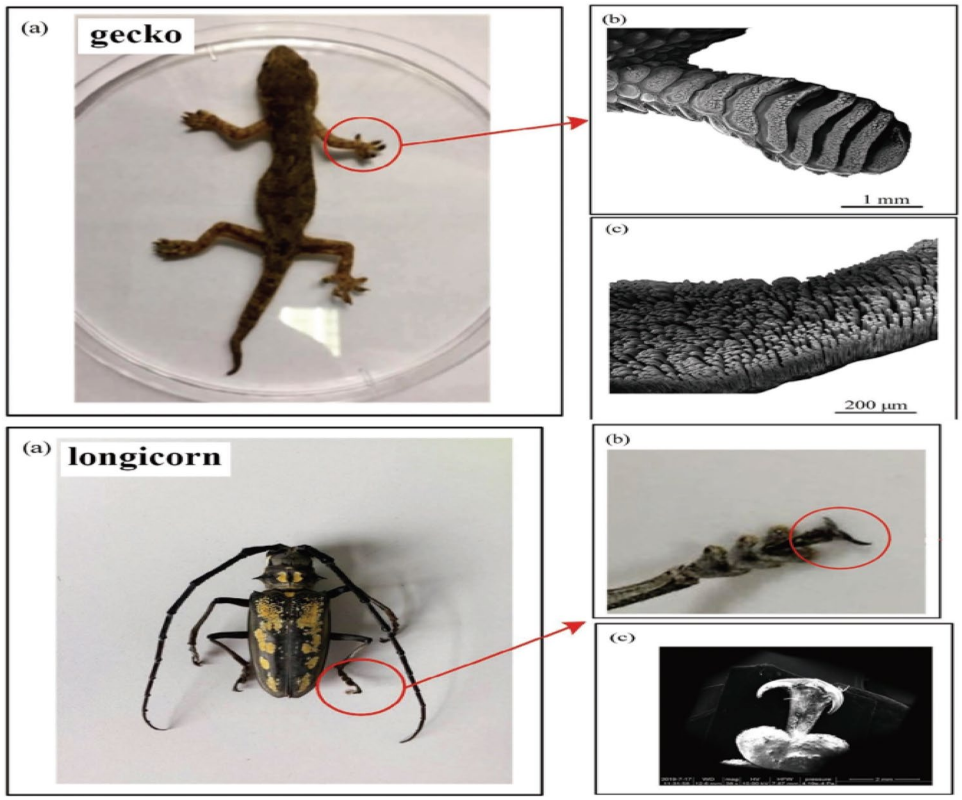


**Fig. 8** Bionic adsorption method [168]

adhesive surface (polydimethylsiloxane (PDMS)) and an unstructured support layer [162, 163]. The adhesive material using polydimethylsiloxane is novel and reusable to replace the traditional walking mechanism. Robots with the surface structure of gecko feet combined with adsorbent materials can move stably on walls [54, 164, 165]. Bian developed a composite wall-climbing robotic palm. The 3D printed palm consists of a suction cup, five hooks, and a series of bionic bristles. The biomimetic adsorbent was fabricated using polymer printing lithography. A ring of bionic bristle array material cures on the edge of the suction cup to enhance adhesion. The bionic bristle array material on the palm is better adapted to smooth surfaces, while the hooks are used to attach to rough surfaces. This composite palm has been well tested on smooth, wet, and rough surfaces [166]. Aksak et al. introduced the preparation, characterization, and testing of biomimetic synthetic dry glue fibre arrays. The fibre is prepared by the micro-moulding method, and then the blade tip is formed by dipping. This robot can climb a distance on painted walls and wooden doors [167].

At present, the bionic adsorption wall-climbing robot can walk on clean and smooth glass or wall surfaces, but when moving on rough and complex wall surfaces, this requires the dry glue adhesive to be resistant to foreign objects such as dust and oil. In this case, It can mimic other biological mechanisms such as flexible claws and spines [169–171]. The RiSE of Illinois Institute of Technology used a claw attachment method. The robot's feet are flexibly arranged with a series of claws, which increases the probability of contact between the claws and the wall. Moreover, the robot's feet can sense whether its state is stable when attached to the wall through the pressure sensor [97]. Similar to RiSE, each claw spur of Spinybot II has ten flexible claw spurs. The claw spurs are made of rigid and flexible materials by deposition manufacturing technology. These spurs can be well captured to the surface of the asperities [172]. The rock climbing robot LEMUR IIB, designed by the California Institute of Technology, uses micro-grippers arranged in a layered array to grip the rock. The micro-grippers are compliant devices made of sharp hooks and flexible elements. Each hook can move independently. There is a chance to grab the rough surface of the rock [173]. The foot mechanism of CLASH at the University of California, Berkeley consists of a four-bar mechanism, with the top link mechanism attached to the leg and the bottom link mechanism extending forward with embedded claws. The design of the mechanism allows the claw to quickly rotate and hook the surface when it comes into contact with the contact surface [174, 175]. The hexapod micro-robot of Chiba University in Japan is equipped with two directional claw units with four claws on each leg. A spring made of shape memory alloy drives the claws against the wall through electric heating and cooling [176]. Ji et al. draws on living beings' outstanding movement ability and attachment characteristics, combined with soft rubber pads and fish hooks, designed a flexible hook and claw foot structure and successfully applied it to a four-legged hook and clawed wall-climbing robot [177]. Bian proposed a new type of wall-climbing robot suitable for rough or smooth surfaces. The robot's bionic palm uses a unique bionic hook inspired by the longhorn beetle and a bionic bonding material inspired by gecko. It uses 3D printing technology to make a unique bionic hook and polymer printing lithography to make a bionic adhesive material. These two different bionic attachment attachments are used in the palm of the robot to achieve climbing on different surfaces [168]. Small multi-legged animals can climb vertical walls with rough surfaces. For example, spiders can form emergency behaviors entirely based on the environment, including rigid body interaction, grip recovery, and adaptive wall climbing [178]. Choi et al. inspired by cockroaches, proposed a small, lightweight wall-climbing robot with a single drive. To ensure reliable wall climbing, the contacts of the two tripods overlap accordingly. The design of the quick return leg allows the phases to overlap without the need for additional drivers [179].

Insect tarsal bones play a vital role in the climbing performance of insects. The segmented structure of the tarsal bone makes it more flexible to adapt to irregular surfaces and makes the attachment more reliable [180]. The Oriental silk moth (Serica Orientalis Motschulsky) is a leaf-eating insect that can climb on leaves, tree trunks, and rough outer wall surfaces. Liu proposed a crawler wall-climbing robot with bionic vertebral feet. The robot's trajectory consists of more than a dozen vertebral feet, which are attached to rough surfaces, and the adhesion performance can be improved [81]. The barbed toe pad is designed based on the insect's tarsal system. Chen proposed a method to measure the clamping force of a biped wall-climbing robot with barbed toe pads. Each foot of the robot consists of a pair of opposing linear thorn-like arrays [181]. Insect pads (such as ants and stick insects) can produce adhesion that is several times their weight [182]. Arthropods like stick insects use their moist attachment pads to crawl on vertical surfaces with excellent locomotion performance. He et al. analyzed the wet adhesive mechanism based on the insect pad's shape, explored a micro-structure wet pad that combines electroforming and soft lithography, and applied it to the design of a hexapod climbing robot prototype. Experimental results show that it can climb inclined surfaces and statically stick to vertical surfaces [183].

The wall-climbing robot relying on the bionic mechanism and bionic adsorption material can be stably adsorbed on the vertical wall without external force. The development of bionic adsorption methods has expanded the application scope of wall-climbing robots and improved their obstacle-surmounting capabilities.

### 3.4 Electrostatic Adhesion

When an object with static electricity is close to another object with no static electricity, due to electrostatic induction, the side of the object without static electricity that is close to the object with static electricity will accumulate charges of opposite polarity to the charge carried by the charged object, because the opposite charges attract each other, it will show the phenomenon of "electrostatic adsorption" [184, 185]. The research on electrostatic adsorption materials and technologies has improved the electrostatic adsorption capacity, and therefore, its application in wall-climbing robots is also increasing [186–188]. Figure 9 shows a wall-climbing robot with electrostatic adsorption.

Chen proposed a theoretical model to analyze the dynamic properties of electrostatic adhesion on dielectric materials. A crawler wall-climbing robot based on an electrostatic adsorption mechanism is designed. Experiments were carried out on the climbing performance of the robot on different walls. The results show that the robot can successfully achieve linear motion. The downside is that the robot can only achieve steering movements on glass surfaces with an inclination angle of about 30°. Chen, R based on the electrostatic adsorption technology, a four-legged electrostatic adsorption wall-climbing robot is designed by imitating the shape of a gecko. The robot can achieve stable straight-line climbing and turning actions on the surface of high-rise glass windows [189, 190, 194–196]. Prahlad introduced a novel flexible electro-adsorption technology for wall-climbing robots. The advantage of this adsorption method is that it uses very little power and exhibits the ability to repeatedly adsorb on walls heavily covered with dust or other debris [197]. Yamamoto uses plastic films and conductive foils to create flexible electrodes for use as suction devices for wall-climbing robots. Test results show that the robot can successfully climb the conductive wall at a speed of 6.6 mm/s. In addition, surface precharge and comb electrodes are used for flexible electrodes for adsorption on glass surfaces with non-conductive properties. The robot climbed at an average speed of 1.75 mm/s in the experiments [191]. Keng used a flexible elastic material as a dielectric to enhance the performance of electrostatic adhesion for climbing on featureless surfaces. Combined with a novel multi-stage manufacturing process of layered hybrid adhesives using blade coating technology, an orbital motion solution that simultaneously utilizes static electricity, elastomer adhesion, and tail forces is proposed. The robot can climb an 80° slope at 4 cm/s on a smooth surface. Furthermore, hybrid adhesives can work on surfaces with roughness values within 300 nm [193]. Sabermand uses thin, flexible electrodes made of aluminum foil as the adsorption device for the wall-climbing robot, and the whole machine weighs 1.27 kg. The electrode is flexible enough to increase the contact area and adapt to the

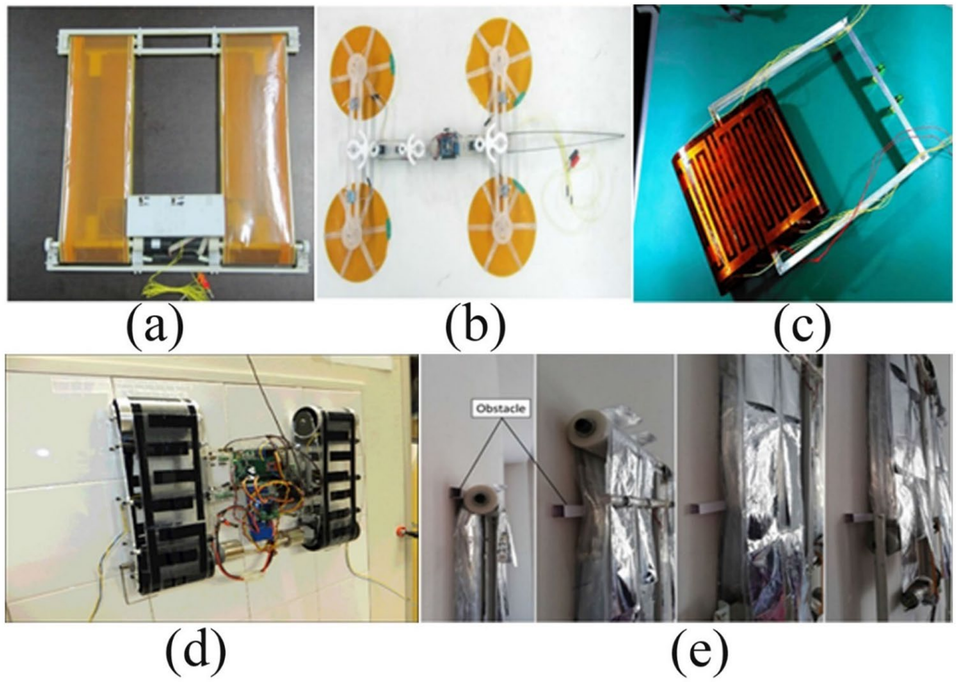


**Fig. 9** Wall-climbing robot with electrostatic adsorption. **a** Ref. [189], **b** Ref. [190], **c** Ref. [191], **d** Ref. [192], **e** Ref. [193]

wall's shape and roughness. Extensive experiments have successfully demonstrated the robot's ability to stably adhere to walls of different materials, including wood, plaster, granite, and glass. In addition, obstacles of different heights can be crossed. It can carry an additional load of 14 N when adsorbing on vertical walls [192].

Electrostatic adsorption can make the wall-climbing robot lightweight, integrated and miniaturized. Moreover, electrostatic adsorption has lower requirements on the wall surface. It can be adsorbed on the smooth wall surface of glass material or the rock wall surface with high surface roughness, which significantly promotes the development of wall-climbing robots.

## 4 Research on Motion Control Technology of Wall Climbing Robot

The motion of a wall-climbing robot is a complex problem, and the stability of its motion on the wall has always been the most critical research content. For example, the steering mode of the crawler-type wall-climbing robot is slip steering, which can be achieved by controlling the speed of the crawlers on both sides. The relationship between the change in slip rate caused by each crawler's speed and the crawler system's driving force is crucial in controlling the robot's steering [198]. Therefore, the slip must be included in the dynamic model to improve motion accuracy in trajectory control [199]. Because wall-climbing robots often work in dangerous environments and must work reliably, the control system is getting more and more attention. Qian et al. designed and implemented a prototype of a non-driven glass curtain wall cleaning robot based on the typical characteristics of the high-rise building's glass curtain wall. The robot relies on its gravity and the lifting force of the trolley crane on the roof to move while using double vacuum suction cups to attach to the glass surface. When cleaning, it can cross obstacles such as horizontal window frames. The control system adopts a two-level computer control strategy to realize the robot's movement, cleaning, and surmounting obstacles. The entire control system is based on a master–slave controller; the master controller is located in the portable monitor using wireless communication. As the local control system of the crane, Programmable Logic Controller (PLC) performs all actions on the roof, including the unwinding of the wire rope, protection, and self-positioning of the lateral movement along the outer wall of the building [200]. Gradetsky introduced the control system structure of a wall-climbing robot with a vacuum contact device to realize movement along vertical, sloped surfaces and ceilings. The main scheme of the vacuum contact device is to adapt to the surface through force, pressure, tactile sensors, and a feedback loop. The information is transmitted from the sensor to the microprocessor of the control system, and a discrete control algorithm based on the dynamic information parameters of the vacuum contactor is proposed [201]. Tavakoli used accelerometers and fibre optic flow sensors to reduce the problem of Omni-directional wall-climbing robots slipping during motion by turning off position closed-loop control to compensate for errors caused by slippage and improving path tracking through control algorithms [202]. The research on the motion control of wall-climbing robots is not only a simple control of the kinematics model. Although the kinematics controller can simplify the tracking problem of non-holonomic constraint systems [203, 204], it is also necessary to integrate other intelligent algorithms to study wall-climbing robots—dynamic performance and control technology.

At present, most wall-climbing robots can realize wireless remote control through the communication protocol of wireless conversion to realize data exchange, increasing the range of robots and increasing the application fields. Based on wireless control intelligent control, the control methods of the robot can be more diverse [112, 205]. As shown in Fig. 10, Dian et al. proposes an intelligent discrete algorithm for trajectory tracking control to realize the precise motion control of the magnetic wheel wall-climbing robot. Improved dual heuristic dynamic programming (DHP) is a trajectory tracking control algorithm that uses random vector functions to connect neural networks (RVFL NNs) with actor key structures. Furthermore, it uses a genetic algorithm to optimize the input layer weights of random vectors to a functional link neural network. The trajectory tracking control algorithm of the wall-climbing robot was simulated, tested, and compared with the neural network tracking control algorithm. Through comparative analysis, the effectiveness and advancement of this method are verified [62]. An extreme working environment requires higher maneuverability to reach the area of interest. Albee et al. detailed the algorithmic solution of A* global planning and optimization problems, established a kinematic climbing planning framework, and regarded it as a discrete The optimal planning problem is achieved on a hardware demonstration test bench to successfully identify, navigate and climb any vertical wall [101]. To avoid the inefficiency of the bionic neural network in completing the coverage path planning, Chen proposed an improved method for the wall-climbing robot to complete the coverage path planning with minor energy consumption. In addition, an energy consumption model is established, and an improved neural network algorithm is used to propose the next step selection strategy from the perspective of the optimal global energy consumption. The results show that it can effectively perform the coverage task [206]. Dung proposed a motion planning algorithm for a humanoid wall-climbing robot using the graph clustering method. This algorithm, called the "Right-Hand Search Algorithm" (RHSA), finds the optimal walking path in coordinates at each moment, analyzes whether the target is still useful, and takes into account the specific capabilities of the robot [207]. Stereo vision's real-time obstacle avoidance method has been widely used because of wall-climbing robots' working environment and characteristics. Huang proposed a homophonic point matching algorithm based on the correlation between regions and boundaries to improve the accuracy and speed of parallel binocular stereo vision and established a mathematical model of parallel binocular stereo vision. The results show that this method has better characteristics of reducing processing data, improving obstacle avoidance speed, and can efficiently and reliably realize obstacle avoidance [208].

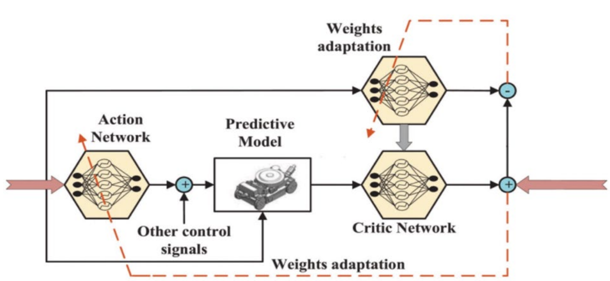


**Fig. 10** DHP structure [62]

It is crucial to study the control of wall-climbing robots. The robot's trajectory planning and motion obstacle avoidance control on the wall can effectively avoid dangerous situations such as falling. In addition, the identification and modeling of unstructured environments can expand the application field of wall-climbing robots.

## 5 Discussion

The wall-climbing robot must have two primary functions: the moving function on the wall and the adsorption function. Figure 11 shows the classification of wall-climbing robots in this paper. The movement mode is divided into three categories, namely wheeled, crawler, and legged. The adsorption method can be mainly divided into negative pressure adsorption, magnetic adsorption, bionic adsorption, and electrostatic adsorption.

Table 1 briefly lists the advantages and disadvantages of the three mobility modes. In terms of motion, the advantage of the wheeled mechanism is that it can move and rotate flexibly, so the wheeled walking mechanism is more efficient. However, the wheel has a small contact surface with the wall, leading to buckling problems when crawling on uneven surfaces. In addition, wheeled mechanisms have difficulty overcoming the effects of slippage that may occur during travel.

The crawler-type wall-climbing robot has a sizeable frictional contact area, which ensures that the robot moves and turns more smoothly on the wall. It has good traction and adhesion performance and can carry more loads, but the fly in the ointment is that due to the larger friction on the wall, it increases the resistance of the robot when turning, and it is not as flexible as the wheeled type. Compared with the

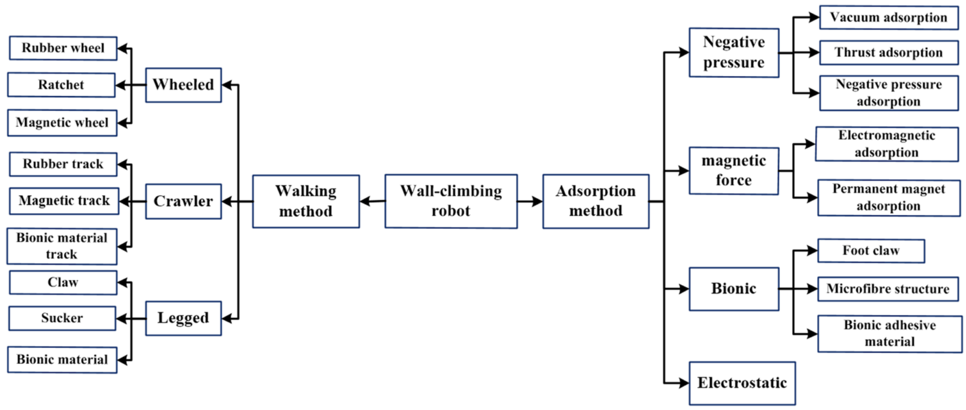


**Fig. 11** The classification of wall-climbing robots

**Table 1** The advantages and disadvantages of different mobility methods

| Mobile device | Advantages | Disadvantages |
|---|---|---|
| Wheeled | Mobile flexibility<br>High efficiency | Poor wall adaptability |
| Crawler type | Stable wall motion<br>Strong wall adaptability<br>High load capacity | Difficult to repair<br>Heavy |
| Legged | Strong ability to overcome obstacles<br>Strong adaptability<br>Many degrees of freedom | Weak carrying capacity<br>Poor stability<br>Difficult to control |

wheeled mechanism, the crawler-type wall-climbing robot can overcome obstacles and maintain stable movement on uneven walls.

The main advantages of wall-climbing robots driven by different bionic mechanisms such as legs and feet include good adaptability to walls and the ability to cross obstacles and recessed areas. In addition, a right-angled transition from the floor to the wall is possible. However, due to the high degree of freedom of the mechanism, the mechanical structure is very complex, the gait control is complicated, and the system stability is poor. The mass of the robot is also relatively large, and the joints bear a lot of force. The movement speed of the leg-foot structure is relatively low compared to other forms of movement. Compared with wheeled and crawler types, the legged design has a stronger ability to adapt to rough terrain; the foothold of the legged robot is discrete, and the robot can choose the best support point within reach. Even if the surface is irregular, you can walk freely with a strict selection of support points. It is precisely because of the diverse foot structure and flexible movements that it is suitable for various shapes of walls. Therefore, the bionic leg-foot design will have better application prospects in wall-climbing robots.

The advantages and disadvantages of the four adsorption methods are shown in Table 2. Negative pressure adsorption includes vacuum, suction cup negative pressure adsorption, and propeller thrust adsorption. Vacuum adsorption is further divided into two structural forms, single-suction cup and multi-suction cup [209, 210], which have the advantage of not being limited by the wall material. However, it needs to be used on relatively flat walls. When the wall has cracks or unevenness, it is easy to cause the suction cup to leak air,

**Table 2** Advantages and disadvantages of different adsorption methods

| Adsorption method | Advantages | Disadvantages |
|---|---|---|
| Negative pressure adsorption | Wide range of application<br>Not limited by wall materials | Louder noise<br>High tightness requirements<br>High requirements for wall flatness |
| Magnetic attraction | Simple structure<br>Strong adsorption<br>Strong adaptability to the wall | Only applicable to the magnetic wall |
| Bionic adsorption | No need for extra power<br>Strong adaptability to the wall | Poor maneuverability<br>Complex design and manufacturing<br>High cost<br>Low load carrying capacity |
| Electrostatic adhesion | Lightweight<br>Low energy consumption<br>Simple structure<br>Wide range of applications | Slow-moving speed<br>Low load capacity |

reduce the adsorption capacity and bearing capacity, and cause a fall accident. In the case of maintaining the stable operation of the wall-climbing robot, the negative pressure environment generated by the rapid rotation of the fan or propeller will be accompanied by loud noise. Therefore, the disadvantage of negative pressure adsorption is that it is noisy and requires high sealing performance. It requires external energy to generate negative pressure and increase system power consumption.

The magnetic adsorption wall-climbing robot has two adsorption methods: electromagnetic adsorption and permanent magnet adsorption. The electromagnet type requires electricity to maintain the adsorption force, but the operation and control of the robot are relatively convenient. The permanent magnet type is not affected by power failure and is reliable in use, but it is more troublesome to control than electromagnetic adsorption. The wall-climbing robot of the magnetic adsorption method does not have high requirements on the flatness of the wall surface, and the adsorption force is much greater than that of other adsorption methods. But the premise is that the wall must be a magnetic material, which is only suitable for metal walls, which severely limits the application of the wall-climbing robot environment.

The advantage of biomimetic mechanism adsorption is that the adsorption mechanism does not require additional power, and it is suitable for rough or structured surfaces. The claw-stab bionic mechanical mechanism robot will not cause adsorption failure even when the power is cut off. On the other hand, this bionic design doesn't move very fast. In addition, there will be the problem that the bionic adsorption material and the wall surface are difficult to separate. Designing and manufacturing the bionic mechanism and material is complicated and expensive. In addition, the load capacity is low compared to robots using magnetic adsorption or negative pressure adsorption.

Electrostatic adsorption can be applied to conductive and non-conductive walls on smooth and rough surfaces, with strong adaptability and wide application. Also, it can work in a vacuum environment. The electrostatic adsorption device is simple in structure, integrated, light in weight, and low in energy consumption of the whole machine. However, due to the slow-moving speed and insufficient load capacity of electrostatic adsorption, its practical application in wall-climbing robots is less.

The adsorption structure is an indispensable design in the wall-climbing robot. Among the main adsorption methods of wall-climbing robots, magnetic adsorption and negative pressure adsorption are the more mature technologies. Bionic adsorption and electrostatic adsorption have vast application prospects.

Table 3 categorizes the literature on wall-climbing robots cited in this article according to walking and adsorption modes. The following conclusions can be drawn from Table 3:

1. Judging from the number of studies on the three walking modes, the wheeled walking mechanism's flexibility and manufacturing convenience, the wheeled walking mechanism is the most widely used for wall-climbing robots, followed by the crawler-type and the legged type. It can be seen from Table 3 that the wall-climbing robot of the wheeled walking mechanism mainly cooperates with two adsorption methods: negative pressure adsorption and magnetic adsorption. Research on the bionic wheel primarily focuses on the ratchet structure. Part of the ratchet structure is the bionic claws and thorns of insects and animals, and the other part is combined with bionic adsorption materials to achieve the adsorption effect. The track structure increases the magnetic adsorption area, making the adsorption more stable. Therefore, the crawler-type wall-climbing machine using magnetic adsorption technology is more mature; the leg-foot type has strong adaptability and ability to overcome obstacles, so it is widely used in the three adsorption methods.
2. From the perspective of adsorption methods, the application research of negative pressure adsorption and magnetic adsorption is relatively mature. Biomimetic adsorption technology has good research prospects, but it still needs further development. In the negative pressure adsorption technology, the walking mechanism of the wall-climbing robot is mainly wheeled and legged. The legged mobile wall-climbing robot primarily uses suction cups and vacuum pumps for adsorption. It can be

**Table 3** Statistics of wall-climbing robots with various combined adsorption methods

| | Negative pressure adsorption | Magnetic adsorption | Bionic adsorption | Electrostatic adhesion |
|---|---|---|---|---|
| Wheeled | [13, 27, 39, 40, 51, 56–59, 113, 121, 122, 124–126, 128, 151, 200, 204, 206, 211] | [17, 19, 21–24, 29, 30, 46, 48, 49, 60–63, 138, 150, 151, 153, 212–215] | [55, 69, 216] | |
| Crawler | [33, 71, 108, 109, 111] | [14, 20, 26, 77, 78, 82–86, 205, 217, 218] | [108] | [189, 191–193, 195, 196] |
| Legged pose | [11, 25, 35, 99, 115, 121, 123, 208, 219–223] | [101, 143, 154, 201, 204, 224–226] | [112, 166–171, 179, 181] | [190] |

seen from Table 3 that among the wall-climbing robots of the magnetic adsorption method, the number of studies on the three different walking structures is almost the same, indicating that magnetic adsorption has strong applicability. Since the bionic adsorption technology is adsorbed by the thorn structure of the legs and feet of the bionic insects and the bionic adsorption material, the bionic adsorption mainly cooperates with the leg and foot mechanism to realize the movement of the robot. Most electrostatic adsorption adopts a crawler walking mechanism, increasing the contact area with the wall surface and the adsorption force.

## 6 Research Prospects of Wall-Climbing Robots

The technology development of the negative pressure adsorption and magnetic adsorption methods has been relatively mature. With the emergence of commercial products, they have been widely used in a particular range, but their shortcomings limit the promotion and application of progress. As a kind of innovative bionic material, dry adhesive can adapt to the wall surface of various materials without noise. Although its adsorption capacity is still relatively poor, with the development of Micro-electromechanical Systems (MEMS) processing technology and new materials, the performance of the bionic adsorption method will be significantly improved. To meet the requirements of future industry for wall-climbing robots, we believe that future research trends are possible involving the following aspects:

1. One of the cutting-edge technologies of the twenty-first century is micro-robots. Micro-robots can be used for small-scale pipeline inspection operations, enter the human intestine for inspection and treatment without harming the human body, and enter small and complex environments to perform various functions [227–229]. Small and light robots have less energy consumption and higher flexibility. The component development and energy supply methods of various micro-actuators have laid the foundation for the miniaturization of wall-climbing robots. Therefore, the miniaturization of wall-climbing robots is one of the important development trends in the future [230].
2. Adsorption technology has always been the bottleneck in developing wall-climbing robots, which determines the application range of robots. At present, the research on adsorption methods of wall-climbing robots is becoming more and more mature. Based on the original adsorption methods, research and development [231, 232] include new adsorption methods for new materials such as dry glue and polymer synthetic viscous materials [162, 163]. The development and research of new bionic adsorption technology are indispensable in the current field of wall-climbing robots. The development of biomimetic viscous materials and mechanisms that simulate organisms with good adsorption capacity, such as geckos, is a hot spot in developing new adsorption technologies.
3. There will be wet areas on complex walls. Also, rain can cause slippery walls. For the vacuum adsorption wall-climbing robot, the presence of rainwater will reduce or lose its adsorption capacity. In contrast, the magnetic wall-climbing robot can continue to be attached to the wall, but whether it is a crawler or a wheeled robot, it may be affected by rain. This leads to slippage and difficult driving, limiting the work area. Therefore, the development of electrostatic adsorption technology, biomimetic adsorption materials, and mechanical structures is also essential for the wet adsorption of wall-climbing robots [233–240].
4. Energy issues cannot be ignored. Seek new reliable energy to power the robot and realize the goal of the robot walking outdoors for a long time.

## 7 Conclusion

This paper reviews the research progress of three different motion modes of wall-climbing robots: wheeled, crawler, and legged, as well as the research progress of adsorption technology, mainly including negative pressure adsorption, magnetic adsorption, bionic adsorption, and electrostatic adsorption. The application of the intelligent control algorithm of the wall-climbing robot in the movement process is discussed. The deficiencies in the current research are analyzed, and the future development trend of wall-climbing robots is discussed.

Stable adsorption is crucial for wall-climbing robots. Only stable adsorption can carry its equipment to run efficiently. Therefore, the study of adsorption technology is one of the key parts. Novel adsorption materials and novel adsorption structures based on biomimetic methods are potential and effective approaches. Research on new adsorption technologies such as electrostatic adsorption and bionic adsorption will expand the application field of wall-climbing robots. It is foreseeable that the application of wall-climbing robots in various fields will play an increasingly important role in the future. We hope this article provides valuable information for practitioners in the field.

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## Declarations

**Conflict of interest** Authors declare that they have no competing interests.

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