Self-Compliant Track-Type Wall-Climbing Robot for Variable Curvature Facade

YANG WANG, XIAOJUN ZHANG, MINGLU ZHANG, LINGYU SUN, AND MANHONG LI
School of Mechanical Engineering, Hebei University of Technology, Tianjin 300401, China

Corresponding author: Xiaojun Zhang (xjzhang@hebut.edu.cn)

This work was supported in part by the National Key Research and Development Project of China under Grant 2018YFB1309401, in part by the National Natural Science Foundation of China under Grant 61803142, in part by the Natural Science Foundation Project of Hebei Province under Grant E2018202338, and in part by the Hebei Science and Technology Agency Science and Technology Innovation Strategy Funding Project under Grant 20180603.

ABSTRACT The paper presents a wall-climbing robot featuring self-compliance for variable curvature façades. The high payload and maneuverability make it highly potential in heavy-duty operation of industrial applications. The robot consists of two traction modules and one link module. Each traction module is equipped with magnetic adhesion and crawler traction submodules. The two traction modules are connected by the link module with 4 degrees of freedom (DoF) of passive compliance. Variable curvature façade self-compliance is achieved by the passive compliant link module, which results in the attitude change decoupling of the two traction modules. The attitude can be adjusted under the effect of magnetic adhesion force to comply with the curvature variations. High payloads are achieved by the large contact area between the crawler and the surface. Omni-directional high maneuverability is enabled by the speed difference between the motors of two traction modules. The robot can maneuver in any direction on the surface with a minimum radius of 1 m and carry 36 kg payload on vertical surfaces.

INDEX TERMS Wall-climbing robot, adapting variable curvature, overcoming obstacles, high payloads, high maneuverability, magnetic adhesion.

I. INTRODUCTION

In the past two decades, wall-climbing robots were developed for the inspection and maintenance of oil tanks, wind turbines, and marine vessels, such as inspection for paint corrosion, welding defects and cleaning, derusting, and painting of facade structures.

Reliable adhesion methods are the prerequisite problems to be solved for climbing the surface. The most commonly used adhesion methods at present are by using magnets [1]–[14] or negative pressure [15]–[24]. Other new methods, such as dry adhesion [25]–[31], micro-spines [32]–[35], and electrostatic [36] and [37], have also been developed. Each adhesion method has different types of adhesion. For example, the magnet adhesion usually adopts foot [1] and [2], wheel [3]–[11], and track-types [12]–[14]. Negative pressure has suction [15]–[18], multilink [19]–[21], and propeller-types [22]–[24]. Dry adhesion has adhesive footpads [25] and [26], track [27]–[29], and wheel-leg-type [30] and [31]. Micro-spines feature wheel [32] and claw-types [33]–[35]. Electrostatic type mainly adopts the track-type [36] and [37] to ensure reliable contact with the wall.

The external facade structures of oil tanks, wind turbines, and marine vessels, as the target of this research, have the common characteristics as following:

1) Periodical inspection and maintenance required.
2) Ferromagnetic material needed.
3) Exterior circumference is convex with variable curvature.
4) The surfaces have protruding obstacles, such as welds.

Considering heavy equipment, such as high-definition camera or ultrasonic flaw detector sensor, which is used to complete inspection work, adhesion methods, such as dry adhesion, micro-spines, and electrostatic, cannot provide sufficient adhesion force to guarantee the capacity of payload. Negative pressure lacks reliable adhesion capacity due to the energy consumption and ideal seal of negative pressure chamber. By contrast, magnet adhesion is a more appropriate choice for the ferromagnetic structure, because it provides reliable adhesion force and large payload. In addition, some applications such as painting or cleaning, require the robot...
to scan the whole structure efficiently and fix to a local area quickly. Therefore, high navigation velocity and good maneuverability is desirable.

The varying curvature and the obstacles of the facade are a challenge for wall-climbing robots and thus limit the scope and capabilities of the robot’s operations. The robot should possess capabilities for climbing variable curvature surface and overcoming obstacles to improve its operation ability for inspection and maintenance.

To climb and navigate over the facade with the aforementioned characteristics, the robot should consider:

1) High payload.
2) High maneuverability.
3) High speed.
4) Adaptability to variable curvature.
5) Ability to overcome obstacles.

To possess the aforementioned abilities, a couple of climbing robot-based magnetic adhesion methods have been developed. Muhammad developed an inchworm-inspired crawling robot-“iCrawl”[1], which is biped-type with 5 DoF, to crawl on the metal pipe surfaces. The special design of the foot-caps with electromagnets gives the iCrawl adaptability and stability for crawling on metal pipes under various curvatures. Fabien Tache et al. developed a compact magnetic wheeled robot-“Magnebike”[4], for inspecting complex-shaped pipe structures. Magnebike can pass 90° convex obstacles and follow a circumferential path of the pipe because of its flexible 5 DOF. The series of “Omni-Climbers,” developed by Mahmoud Tavakoli [9] and [10], is a successful implementation of an inspection robot for ferromagnetic structures. This robot uses flexible chassis for a better adaptability to the curvature without actuation or using omni-directional wheels for its good maneuverability. Payload capacity is important in climbing robot applications for heavy industries. The magnetic climbing robots with the foot and wheel-type have capabilities for climbing variable curvature surface and overcoming obstacles. However, the capacities of high payload and maneuverability are unavailable for the robot based on foot or wheel-type. Wall-climbing robot using magnetic adhesion based on track-type has a good payload capability due to the large contact area between the track and the wall. For example, Lee et al. developed a new climbing robotic mechanism—“Com-bot” for high-payload climbing [14]. This mechanism can climb on a vertical surface in upward or downward directions with more than 10 kg payload at a speed of 9 cm/s and it overcomes a 30 mm-diameter obstacle on a vertical surface. However, the maneuverability of the “Combot” is limited by the length of structure, and this limitation results in the lack of flexible turning ability.

Existing techniques enable a certain degree of adaptive variable curvature and the ability to overcome obstacles. However, the wall-climbing robot still fails to adapt to the wall motion under high payload with good maneuverability for some heavy-duty operations. Combined with the payload and motion process of the wall-climbing robot, the wall-climbing mechanism based on permanent magnet adhesion and track-type meets the requirements of some heavy-duty operations on complex curved surfaces.

The main objective of this study is to develop a new climbing robot platform with high payload without complex control. The robot can adapt to varying curvatures and overcome obstacles on complex curvature surface to achieve high maneuverability. The robot adopts permanent magnet adhesion and track-type mobile configuration, which is composed of two traction modules and one link module. Each traction module is equipped with magnetic adhesion and crawler traction modules, which are used for the wall surface adhesion and movement of the robot. The lightweight design of magnetic adhesion module provides sufficient adhesion force to ensure the robot to carry high payload. The two traction modules are connected by link module with 4 DoF, and the attitude changes of each other are relatively independent to improve the adaptability of curvature surface movement. Each traction module is driven by only one motor to achieve omni-directional high maneuverability with different speeds between the two motors.

The rest of the paper is organized as follows. Section II shows the principle of adapting curvature surface of track-type mobile configuration. Section III gives an overview of the structure of the proposed wall-climbing robot, and the adaptive motion of the robot to variable curvature and obstacle overcoming based on the external structure parameters of the wind turbine tower is analyzed in Section IV. The lightweight design of permanent magnet adsorption module is analyzed by finite element analysis (FEA) in Section V for high payload requirements. The prototype and experimental results of the robot are introduced in Section VI. Section VII concludes the paper.

II. PRINCIPLE OF ADAPTIVE CURVATURE SURFACE MOTION

Locomotion mechanisms, such as the wheel and foot-type, have disadvantages of small contact area with the wall, unstable contact, easy slippage, and poor stability in the movement of the facade due to the structural characteristics. However, the locomotion mechanism of track-type is the current best choice for large payloads because of its advantages of large contact area and high stability.

The movements of the robot on the vertical surface are made up of combinations of three basic movement states: longitudinal, lateral, and turning movements. A conventional track-type robot has difficulty making effective contacts with the surface in the three basic movement states due to its solidified posture; this condition can lead to motion failure, as shown in Fig. 1. Thus, ensuring reliable contact between the track and the curved surface is a priority, as shown in Fig. 2. Both track axes need to follow the curvature changes to form a certain angle in the longitudinal movement (Fig. 2a). The track needs to be flexibly deformed to ensure it conforms to the curved surface during lateral movement (Fig. 2b). The posture of the track needs to produce a pitching motion to conform to the undulations of the curved surface in the
turning motion (Fig. 2c). In general, the tracks on both sides need to have relatively independent posture and controlled flexibility to ensure the adaptability and maneuverability of the robot to curved surfaces. Therefore, achieving relatively independent posture changes between the tracks while ensuring the integrity and stability of the robot and cooperation with the permanent magnet adsorption structure is the key to achieve adaptive curvature of the robot.

III. ROBOT DESIGN MECHANISM

The main purpose of this design is to develop a wall-climbing robot with adaptive motion capability. The robot is applied to the operation and maintenance of large steel facades, such as oil tanks, wind turbines, and marine vessels. In addition to having sufficient payload and motion stability, adaptive curvature change of the surface for achieving the flexible relative DoF between each module is used to adapt the modules are connected by link module with 4 DoF. The adhesion and crawler traction modules. The two traction module. Each traction module is equipped with magnetic adsorption mechanism. The role of the driving mechanism is to convert the torque of the alternating current(AC) servo motor into the driving force. As illustrated in Fig. 4a, the torque from the motor is delivered to timing pulley through right-angle reducer. The torque delivered to the timing pulley rotates the timing belt (the torque of the pulley is the driving torque). The rubber, which is outside of the timing belt, greatly increases the friction between itself and the wall of tower; it also protects stripping the coating of the tower by adhesion force. The teeth, which are inside of the timing belt, are removed from the middle part and are kept symmetrically on both sides. Sufficient space is provided for the magnetic adsorption mechanism inside the timing belt to avoid the contact between the permanent magnet and the teeth of the timing belt. It also reduces the distance between the permanent magnet and the surface of the wind turbine tower. Correspondingly, the timing belt pulley structure is composed of two belt wheels and one rim to accommodate such a timing belt, and the two belt wheels are bolted symmetrically to each side of the rim. The belt wheel is engaged with the timing belt, and the rims are stuck on the inside of the teeth of the timing belt. The belt wheel and the rim are provided with lightening hole to reduce the weight of the traction module. These components of the traction module help improve the driving performance.

![FIGURE 1. Conventional track-type robot motion posture on curved surface: (a) longitudinal movement, (b) lateral movement, (c) turning movement.](image)

![FIGURE 2. Adaptive track-type robot motion posture on curved surfaces: (a) longitudinal movement, (b) lateral movement, (c) turning movement.](image)

![FIGURE 3. 3D modeling of the robot configuration.](image)

The robot is simplified, as shown in Figs. 4c–d, to analyze the driving condition. Here, we have:

\[ F_G = \frac{(m + M) g \sin \alpha}{2} \]  
\[ F_f = \mu N \]  
\[ N = 2F_M + \frac{(m + M) g \cos \alpha}{2} \]  
\[ F_f > F_G \]  
\[ F_d = \frac{\tau_d}{r_d} - F_G \]  
\[ F_d < F_f \]  
\[ \tau_d > F_G r_d \]

where \( F_G \) represents the landing force. \( m \) and \( M \) are the masses of the robot and inspection device, respectively. \( g \) is gravitational acceleration, and \( \alpha \) means the tilt angle of the wind turbine tower. \( F_f \) denotes the friction forces between the surface of the tower and the rubber of the timing belt, and \( \mu \) is the friction coefficient of \( F_f \). \( F_M \) is the adhesion force.
Mechanical mechanisms of the traction module and the analysis of the driving condition: (a) driving mechanisms, (b) magnetic adsorption mechanisms, (c) staying on the wind turbine tower stably, (d) Skid state analysis.

2) MAGNETIC ADSORPTION MECHANISM

The magnetic adsorption mechanism provides the adhesion force required by staying and moving on the wind turbine tower. The adhesion force is generated by two permanent magnets with opposite magnetic poles. The yoke is used to constrain the direction of magnetic lines of force for enhancing the adhesion force. The permanent magnet and the yoke are fixed together and installed at the bottom of the magnetic adsorption mechanism. The four groups of pressure pulley structure are installed on both sides of the magnetic adsorption mechanism. Same as the timing belt pulley, the pressure belt wheel meshes with the timing belt, and the rim is stuck on the inside of the tooth of timing belt. The pressure belt wheel and the rim are equipped with lightening hole to reduce the weight of the whole structure. The spindle is used to hold the magnetic adsorption mechanism to the traction module, as shown in Fig. 4b. The adhesion force generated by the permanent magnet is applied with positive pressure to the timing belt by the pressure pulley to ensure the stable attachment of the robot to the tower. Since the magnetic adhesion force is applied along the positive (normal) direction of the timing belt, and no tangential tensile stress is generated, so the belt is not broken.

B. MECHANISMS OF LINK MODULE

The linking module is composed of a main platform and two connecting modules. Four universal wheels are presented on the main platform, and they are used to keep the position between the main platform and the surface of tower in order to stabilize the robot movement, as shown in Fig. 5a. The connection module is made up of the rotation hinge with 2 DoF of pitch and roll, and each traction module is connected with the main platform through the connection module with 2 DoF, as shown in Fig. 5b. This design enables relatively independent attitude flexibility of the two traction modules.

C. ADAPTIVE CURVATURE

The mechanism of traction module for adapting various curvatures is important for the inspection on the wind turbine tower. The main platform is relatively stable with the wall under the support of the universal wheel when the robot moves longitudinally and turns, as shown in Fig. 6. Each traction module can follow the changes in curvature and fluctuations on the surface depending on the 2 DoF of the connecting module.

The direction of adhesion force is determined by the normal direction of the surface. Thus, the magnetic adsorption module is rotated by the changes in curvature when the...
robot moves laterally, as shown in Fig. 7. The timing belt is deformed by the pressure pulley structure, which increases the contact area with the surface and the friction between itself and the tower.

IV. ADAPTIVE MOTION ANALYSIS

The complex facade has many structural features, such as variable curvature and obstacle protrusion, which introduces higher requirements for the motion performance of the robot. The motion characteristics of the flexible adaptive wall-climbing robot under variable curvatures are analyzed with the external structure parameters of wind power tower as an example.

A. ADAPTIVE MOTION WITH VARIABLE CURVATURE

The radius $r$ of circumferential curvature of the outer surface of wind power tower tube varies from 1 m to 2.5 m, and the robot can realize self-adaptive movement on the wall with different attitudes. The robot mechanism is designed symmetrically. Thus, the attitude changes of the unilateral motion adsorption module are analyzed as follows:

1) LONGITUDINAL MOVEMENT

The structure diagram of the adaptive longitudinal motion attitude of the robot based on the previous description is shown in Fig. 8. Given that the support comes from the universal wheel, the center point $B$ of the balance module remains relatively fixed with the center of surface $O$; the center point $A$ of the track follows the changes in curvature $r$ under the action of adsorption; $O_1$ is the center of the turning axis $\omega_1$; the attitude rotation angle $\alpha_1$ is the attitude change of the track module due to the changes in curvature. Then, $\alpha_1$ is calculated as follows:

$$\alpha_1 = \pi - \beta - \gamma$$  \hspace{1cm} (10)

where $\beta$ is the acute angle between linkage $l_{AO_1}$ and $l_{OO_1}$, and $\gamma$ is the acute angle between linkage $l_{BO_1}$ and $l_{OO_1}$.

According to the geometric relationship, $\beta$ and $\gamma$ can be expressed as the trigonometric function of radius $R$ of curvature as follows:

$$\tan \beta = \frac{h_1 + r}{l_1}$$  \hspace{1cm} (11)

$$\tan \gamma = \frac{h_2 + r}{l_2}$$  \hspace{1cm} (12)

where $h_1$ and $h_2$ are the normal distance of points $A$ and $B$ from the wall surface, respectively; $l_1$ is the length of $AO_1$, and $l_2$ is the length of $BO_1$.

According to Equations (10)-(12), the function of $\alpha_1$ with respect to radius $r$ of curvature is calculated as follows:

$$\alpha_1 = \pi - \arctan \frac{h_1 + r}{l_1} - \arctan \frac{h_2 + r}{l_2}$$  \hspace{1cm} (13)
2) LATERAL MOVEMENT

The structure diagram of the adaptive lateral motion attitude of the robot is shown in Fig. 9. The direction of magnetic adsorption force $F_m$ is always along the normal direction of the wall and points to the center $O$ of the curved surface circle. The direction of the adsorption force changes with the radius variations of curvature. $O_3$ is the center of the turning axis, $\omega_3$ of the adsorption module, and the attitude rotation angle $\alpha_3$ is the attitude change of the permanent magnet adsorption module due to the changes in curvature. The track is forced to be flexible and in reliable contact with the surface because of the positive pressure of the belt pulley.

According to the geometric relationship, the function of $\alpha_3$ with respect to radius $r$ of curvature is calculated as follows:

$$\alpha_3 = \arcsin \frac{l_3}{h_3 + r} \quad (14)$$

where $\alpha_3$ is the angle between the direction of adsorption force and the vertical direction, $l_3$ is the length of $CO_3$, and $h_3$ is the normal distance of points $O_3$ from the wall surface.

According to Equations (13)-(14), the curves of the attitude angle $\alpha_1$ and $\alpha_3$ vary with the curvature radius $r$ respectively, as shown in Fig. 10, when the robot moves vertically and laterally on the wall surface with variable curvature. The figure shows that the attitude angles $\alpha_1$ and $\alpha_3$ will decrease to different degrees while the curvature radius $r$ increases. It ensures the robot to be adapted to the changes in curvature in an appropriate attitude.

3) TURNING MOVEMENT

The track on both sides rotates $90^\circ$ around the center point $B$ of the balance module in reverse to the same speed, and the robot changes from the longitudinal motion attitude to the lateral motion attitude. During the process, the center point $B$ of the middle platform remains fixed relative to the wall. However, rolling and pitching motions occur on the attitude of the motion adsorption modules on both sides due to surface fluctuation, that is, $\alpha_1'$ and $\alpha_2'$ both participate in attitude changes.

Firstly, the attitude angle $\alpha_1'$ involved in the rolling motion is analyzed, as shown in Fig. 11. The robot turns angle $\theta$ around the center point $B$, and $h_1'$ changes due to the surface fluctuation, which is the height of point $A$ at the center of the track relative to point $B$. It is used to calculate the changes of attitude angle $\alpha_1'$ in the rolling motion.

When $\theta = 0$, the robot is in longitudinal motion posture. $l_{BD}$ is the distance between hinges $B$ and $D$, which can be calculated as follow:

$$l_{BD} = l_2 + l_1 \cdot \cos \alpha_1 \quad (15)$$

When $0 < \theta \leq 0.5\pi$,

$$l_{BD'} = l_{BD} \cdot \cos \theta \quad (16)$$

$$h_1' = (r + h_2) - \sqrt{(r + h_1)^2 - (l_{BD'})^2} \quad (17)$$

On the basis of the geometric relationship, $\alpha_1'$ is calculated as follows:

$$\alpha_1' = \arcsin \frac{h_1'}{l_1} \quad (18)$$

Then, the attitude angle $\alpha_2'$ involved in the pitching motion is analyzed, as shown in Fig. 12. $O_{31}$ and $O_{32}$ are the axial centers of two groups of adsorption modules, respectively. $h_{31}$ and $h_{32}$ are the height of point $O_{31}$ and $O_{32}$ relative to point $B$. When the track is in the pitching motion, the height changes...
of $h_{31}$ and $h_{32}$ are different due to the surface fluctuation. This height difference can be used to calculate the change in attitude angle $\alpha'_2$ in the pitching motion.

When $\theta = 0$,

$$l_{BD_{31}} = l_{BD_{32}} = \sqrt{l_{BD}^2 + l_3^2}$$  (19)

where $l_{BD_{31}}$ is the distance between the hinges $B$ and $D_{31}$, $l_{BD_{32}}$ is the distance between the hinges $B$ and $D_{32}$, and $l_3$ is the distance between the hinges $D$ and $D_{31}$.

The angle $\theta_2$ between $l_{BD}$ and $l_{BD_{31}}$ is defined as follows:

$$\theta_2 = \arctan \frac{l_3}{l_{BD}}$$  (20)

When $0 < \theta \leq 0.5\pi$,

$$l_{BD_{31}}' = l_{BD_{31}} \cdot \cos(\theta + \theta_2)$$  (21)
$$l_{BD_{32}}' = l_{BD_{32}} \cdot \cos(\theta - \theta_2)$$  (22)

$$h_{31} = (r + h_2) - \sqrt{(r + h_1)^2 - (l_{BD_{31}}')^2}$$  (23)

$$h_{32} = (r + h_2) - \sqrt{(r + h_1)^2 - (l_{BD_{32}}')^2}$$  (24)

On the basis of the geometric relationship, $\alpha'_2$ is calculated as follows:

$$\alpha'_2 = \arcsin \frac{h_{32} - h_{31}}{2l_3}$$  (25)

According to Equations (13) and (15)–(24), the curve of the rolling attitude angle $\alpha'_1$ and the pitching attitude angle $\alpha'_2$ are shown in Fig. 13 with the changes in turning angle $\theta$ and radius of curvature $r$ when the robot makes the turning movement on the facade with variable curvature.

As shown in Fig. 13a, the rolling attitude angle $\alpha'_1$ gradually decreases with the increase in turning angle $\theta$, and the amplitude of attitude transformation also decreases gradually with the increase in radius of curvature $r$.

Fig. 13b shows that the pitching attitude angle $\alpha'_2$ presents an undulating trend with the increase in turning angle $\theta$ and reaches its maximum value when $\theta = 0.25\pi$. At the same time, amplitude of attitude transformation also decreases gradually with the increase in radius of curvature $r$.

B. ADAPTIVE MOTION WHILE OVERCOMING OBSTACLES

The track module’s mechanism of overcoming obstacles is important for operations on the facade. The robot is capable of stable adsorption and can overcome obstacles due to the rotational freedom of the permanent magnet adsorption module (Fig. 14). In the process of robot climbing, the front pressure pulley of the first group of permanent magnet absorption structure contacts and crosses the obstacle under the action of adsorption and traction forces. The gap between the permanent magnet and the wall surface ensures that the obstacle...
V. PERMANENT MAGNET ADSORPTION MODEL
The attitude is adjusted in the process of the robot adapting to the variable curvature facade. The magnetic gap between the permanent magnet and the facade is also changed, which results in the changes in the adsorption force. The thickness of the wall also impacts the adsorption force. Therefore, it is necessary analyzing the changes in the adsorption force during the movement process in combination with the wall structure parameters.

A. MAGNETIC CIRCUIT DESIGN OF CLEARANCE PERMANENT MAGNET ADSORPTION MODEL
To ensure a high payload–weight ratio of the robot, the material properties and magnetic circuit design of permanent magnets should meet the following requirements:

1) The permanent magnet should have a large magnetic energy per unit volume.
2) The magnetic circuit of the permanent magnet should be designed to realize the convergence of magnetic lines of force on one side to reduce magnetic leakage given that the robot is attached to the wall on one side.
3) The adsorption structure should be small in size and light in weight while satisfying the demand for adsorption capacity because of the limitation in the requirements of the volume and quality.

NdFeB-N48 is selected as the material of permanent magnet based on the aforementioned design considerations. NdFeB-N48 has been widely used because of its excellent magnetic properties, such as large magnetic energy product, high stability, large operating temperature range, and strong toughness. Its parameters are shown in Table 1.

The permanent magnet adsorption structure consists of two permanent magnets of the same size and a yoke of pure iron, and it is arranged as shown in Fig. 15. The magnetizing directions of the two magnets are opposite, and the overall depth of the permanent magnet adsorption is 48 mm. The section parameters are shown in Table 2. The material of the magnetic permeability wall is Q235 steel, and the area of the wall is assumed to be infinite.

### Table 1. Parameters of NdFeB-N48.

| Symbol | Parameter                                | Value   |
|--------|------------------------------------------|---------|
| $B_r$  | Remanence induction intensity            | 1380–1420 mT |
| $H_c$  | Coercive force                           | 923 kA/m |
| $B_{max}$ | The maximum magnetic energy             | 366–390 kJ/m³ |
| $T_{op}$ | Operating temperature                     | < 80°C  |

### Table 2. Permanent magnet adsorption structure parameters.

| Symbol | Parameter         | Value |
|--------|-------------------|-------|
| $W_y$  | Yoke iron width   | 60 mm |
| $H_y$  | Yoke iron thickness | 12 mm |
| $W_m$  | Permanent magnet width | 28 mm |
| $H_m$  | Permanent magnet thickness | 20 mm |
| $W_p$  | Permanent magnet distance | 4 mm  |
The distribution diagram of the magnetic lines of force is shown in Fig. 16a. It constitutes a closed loop between the yoke, permanent magnet, wall, and air gap. Moreover, only a small amount of magnetic flux leakage occurs on the sides of the permanent magnet. The magnetic field intensity distribution is shown in Fig. 16b. The magnetic field intensity in the upper area of the permanent magnet structure can be considered as zero. Most of the magnetic fields are concentrated in the permanent magnet and the magnetic permeability wall. The adsorption force also reaches the maximum in this area along which is in positive proportion to the magnetic field intensity.

In the process of the robot moving on the wall with variable curvature, the air gap thickness between the permanent magnet and the wall will change as robot does turning or obstacle jumping, which will affect the adsorption capacity. The calculation model is provided in Fig. 17a. The adsorption force drops sharply as the air gap between the permanent magnet and the wall increases. When the air gap reaches 6 mm, the adsorption force declines slowly. Therefore, the changing range of the air gap distance in the structural design needs to be limited to a reasonable range according to the requirements of the adsorption force to avoid the sudden drop of the adsorption force caused by an excessive air gap that causes the robot to slip or even fall. The changes in wall thickness will change its saturation degree to the magnetic flux, which will affect the adsorption force. The adsorption force under different wall thicknesses is shown in Fig. 17b. The adsorption force will increase with the increase of the wall thickness. When the thickness reaches 5 mm, the magnetic circuit reaches saturation state due to the magnetic intensity limits of the permanent magnet, and the adsorption force is stable at nearly 592 N.

VI. EXPERIMENTAL VERIFICATION

A. PROTOTYPE AND TEST PLATFORM

The robot is prototyped in accordance with the selected design parameters, as shown in Fig. 18. The AC servo motor model of the robot is LS-AMP-SB02ADK3, the right-angle reducer model is ZPLE-060, and the tracked is 14M arc tooth synchronous belt. Most of the materials are aluminum to balance the relationship between the mass of the robot and the strength of the structure, and the parts such as the rotating shaft under local stress are made of steel. At the same time, the variable curvature elevation test platform is fabricated. Detailed parameters of the prototype are shown in Table 3.

The test platform imitates the structural parameters of the top of the wind power tower tube in a 1:1 scale. The total height of the platform is 3 m, and the material is Q235 steel. The top radius is 1 m, and the thickness is 10 mm. The bottom radius is 1.3 m, and the thickness is 20 mm.

B. ADSORPTION FORCE AND PAYLOAD CAPACITY ANALYSIS

The adsorption capacity of the permanent magnet adsorption module is tested using a tensile testing machine. The test
TABLE 3. Prototype test parameters.

| Parameters        | Unit | Value                          |
|-------------------|------|-------------------------------|
| Size              | mm   | 625×573×303                   |
| Mass              | kg   | 24                            |
| Payload           | kg   | 36                            |
| Payload-weight ratio |   | 1.44                          |
| Speed             | m/min| 15 (without payload)         |
| Curvature radius  | m    | ≥0.8                          |
| Crossed height    | mm   | 5×10                          |

Steel plate is fixed on the pedestal of the testing machine, and the permanent magnet module is fixed on the moving part of the testing machine. The air gap between the steel plate and the permanent magnet module can be changed by adjusting the upper and lower displacement of the moving part. The adsorption force of steel plates of different thicknesses is obtained by changing different steel plates. The tested adsorption force data are summarized, and the adsorption force test results are obtained.

The thicknesses of the selected steel plate are 3, 5, 7, and 9 mm, and the corresponding adsorption force test values are shown in Fig. 19. When the air gap is less than 5 mm, the adsorption force increases with the increase of the wall thickness. However, when the air gap is greater than 5 mm, the wall thickness has a slight effect on the adsorption force, which is consistent with the simulation results in Fig. 17. When the thickness is 5 mm and the air gap is the same, the simulation value of the adsorption force will be slightly higher than the experimental results. It may be due to that the permanent magnet module entity has more magnetic flux leakage than the ideal simulation model. Thus, the physical structure design needs to be further optimized.

The payload capacity of the robot is tested on the test platform. As shown in Fig. 20, 18 kg weights are carried on the traction modules on both sides of the robot to test its load capacity. The payload of the robot is 36 kg, which is 1.5 times of the self-weight of the robot. Notably, the weight a robot can carry is the sum of its own weight and payload. Thus, the load is inversely proportional to the weight of the robot. In the future research, the weight optimization of the robot will be considered to maximize the load.

C. WALL ADAPTIVE MOTION TEST

The robot is placed on the wall with variable curvature to test its adaptive motion capability under multi-motion state. At the same time, angle sensors are installed on each axis to collect and analyze the changes in attitude angle during the robot’s adaptive motion. The test results are given as follows:
1) LONGITUDINAL MOVEMENT TEST
As shown in Fig. 21a, the balance module remains stable under the action of the universal wheel when the robot moves longitudinally. The motion adsorption modules on both sides adjust their own attitude by using the turning axis $\omega_1$ of the connection module and then realize the adaptive longitudinal motion with variable curvature.

As shown in Fig. 22, the yawing angle $\alpha_1$ of the turning axis $\omega_1$ in longitudinal and lateral movement decreases from $12.3^\circ$ to $9.5^\circ$ as the radius of curvature increases from 1 m to 1.3 m. Moreover, the rotation angle $\alpha_3$ of the rotation axis $\omega_3$ is reduced from 6.2° to 4.8°.

3) TURNING MOVEMENT TEST
As shown in Figs. 23a–d, the relative position of the crawlers on both sides changes with the turning angle when the robot makes a turn. After turning $180^\circ$, the attitude of the robot change 1 from longitudinal to lateral. The change curves of the yawing angle $\alpha_1$ and the pitch angle $\alpha_2$ with the turning angle $\theta$ are measured at the elevation positions with the curvature radii of 1.1, 1.15, 1.2, and 1.25 m respectively, as shown in Figs. 23e and 23f. Compared with that in Fig. 13, the turning motion of the prototype on the wall conforms to the attitude change characteristics of the theoretical analysis.

4) 45° TILT MOVEMENT TEST
The flexibility of the robot in the wall motion is tested by a certain angle of tilt motion. As shown in Figs. 24a–c,
The robot rotates 45° from the longitudinal attitude, the middle platform remains stable, the moving adsorption modules on both sides follow the undulation of the curved surface, and the posture produces flip and pitch movements. The change in the yawing angle $\alpha_1$ and the pitch angle $\alpha_2$ following the radius of curvature is shown in Fig. 24d. The experiment shows that the robot can achieve adaptive variable curvature tilting motion with a stable attitude.

5) WELDING SEAM OBSTACLE MOVEMENT TEST

As shown in Fig. 25, the overall attitude of the robot remains unchanged when the robot passes through the welding seam. Under the action of adsorption force, the two permanent magnetic adsorption modules can use the rotation axis $\omega_3$ and permanent magnetic gap to complete the passive crossing of the welding seam. Accordingly, the self-adaptive obstacle surmount of the welding seam is realized.

In conclusion, the experimental results show that the flexible wall-climbing robot can fully utilize the passive adaptive motion characteristics of its own attitude when facing the change in wall curvature and welding seam obstacles. The robot can also realize the omni-directional and multi-angle large load and high reliability flexible motion on the variable curvature wall.

VII. CONCLUSION

1) A wall-climbing robot with adaptive motion ability for variable curvature wall is developed to improve the motion ability of wall-climbing robot on large complex metal wall. The robot adopts the gap-type permanent magnet adsorption and split flexible crawler movement mode. It also uses the relative DoF between structures to adjust its own attitude according to the changes in the wall curvature. As a result, the adaptive change for wall curvature is realized.

2) Combined with the variable curvature structural parameters of the wall, the trend of the robot’s attitude angle following the curvature change under various motion states is analyzed by theoretical analysis and numerical calculation. At the same time, the attitude changes in the process of welding seam obstacle crossing are also analyzed.

3) A permanent magnet adsorption model is designed and parameterized calculation is conducted on the basis of the requirement of large load and high reliability. The influence of parameters such as air gap and wall thickness on the adsorption force during the curvature change process is analyzed.

4) The experimental results show that the robot can be steadily adsorbed on the wall. It can also achieve stable and reliable movement with large load on the large metal wall with changeable curvature by adjusting its own mechanism and flexible motion attitude. It has moderate obstacle crossing ability as well.

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