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Wall Climbing Robot Using Electrostatic Adhesion Force Generated by Flexible Interdigital Electrodes

Regular Paper

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Abstract Electrostatic adhesion technology has broad application prospects on wall climbing robots because of its unique characteristics compared with other types of adhesion technologies. A double tracked wall climbing robot based on electrostatic adhesion technology is presented including electrode panel design, mechanical structure design, power supply system design and control system design. A theoretical adhesion model was established and the electrostatic potential and field were expressed by series expansions in terms of solutions of the Laplace function. Based on this model, the electrostatic adhesion force was calculated using the Maxwell stress tensor formulation. Several important factors which may influence the electrostatic adhesion force were analysed and discussed by both FEM simulation and theoretical calculation. In addition, experiments on the adhesion performance of the electrode panel and the climbing performance of the robot on various wall materials were carried out. Both the simulation and experiment results verify the feasibility of electrostatic adhesion technology being applied on wall climbing robots. The theoretical model and calculation method for the electrostatic adhesion force proposed in this paper are also justified.

Keywords Wall Climbing Robot, Electrostatic Adhesion, Flexible Interdigital Electrodes, Adhesion Model, Maxwell Stress Tensor

1. Introduction

Wall climbing robots can crawl on vertical walls with certain loads and perform various tasks such as urban reconnaissance, tank inspection and window cleaning by combining the mobile technology for land robots and adhesion technology [1-3]. To design a wall climbing robot, the selection of the adhesion method is one of the most important aspects. Conventional adhesion methods are mainly based on negative air pressure or magnetic force and a lot of work has been conducted so far. Use of air pressure is very common, however it often leads to a large and heavy robot since it always needs to carry a pump or a fan. In addition, considering the problem of sealing, this method can only work on smooth and non-porous wall surfaces. Magnetic adhesion, on the other hand, can be realized by a rather simple structure and can produce a high adhesion force. However, its application is severely limited because it can only work on
ferromagnetic walls. Other adhesion methods have been employed in studies in recent years. A “Dry adhesion” method, which mimics gecko feet with tiny setae, has gained a lot of attention from many researchers and considerable work has been carried out [4]. This method uses Van der Waals force between the artificial tiny setae and the wall surfaces and can offer good clamping force on various wall materials with no residue left behind. However, the artificial tiny setae are very sensitive to dust and moisture on the wall, which may lead to adhesion failure. Moreover, the manufacturing cost of the setae is quite high, which limits the practical application of this novel method to a certain extent. Another biomimetic approach that has been recently pursued is the use of an array of microspines to scale vertical walls that have some inherent surface roughness [5]. While this approach ensures good mechanical contact and is mostly independent of material contaminants or dust on a surface, it is difficult to climb on smooth surfaces with this approach. The adhesion method has become a bottleneck of development and application of wall climbing robots, so there has been a sustained interest in pursuing novel adhesion methods, which can benefit from simplicity, light-weight and work stability of the robots.

In this study, we focus on a novel adhesion method called electrostatic adhesion, which can be applied to wall climbing robots satisfactorily. Electrostatic adhesion uses electrostatic force produced by an electrostatic adhesion voltage, which is applied using an electrode panel. When the electrode panel is positioned near the wall surface, the electric fields set up by the voltage between the electrodes can induce opposite charges on the wall surface and thus cause electrostatic adhesion between the electrode panel and the wall surface. Through our previous work, we concluded that electrostatic adhesion possesses several advantages compared with conventional adhesion methods: 1) high adaptability and a wide applied range. Electrostatic adhesion can be applied to both conductive and non-conductive walls, smooth surfaces and rough surfaces (using flexible electrodes). Furthermore, it can work on non-ferromagnetic walls (overcoming the shortcomings of magnetic adhesion) and in a vacuum environment (overcoming the shortage of negative air pressure adhesion); 2) a simple structure, which benefits the integration, miniaturization and lightness of the robot. Electrostatic adhesion devices only employ a miniature high voltage module and electrode panel of a certain area, which eliminate some heavy and complicated structures, such as magnets in magnetic adhesion and air pumps in negative air pressure adhesion; 3) low energy consumption. Due to the high resistance of the insulation film, the current flowing through the electrode panel is very low, so the energy of the whole adhesion device is very low. Although electrostatic force in a normal environment is not strong compared with magnetic force or air pressure, electrostatic adhesion for wall climbing robots is still appealing due to the above characteristics.

Electrostatic adhesion technology was first widely used in areas of industry, such as the semiconductor industry, exposure systems, CVDs and dry etchers [6-8]. In electrostatic devices that are called electrostatic chucks or electrostatic grippers, it was proven that electrostatic adhesion is effective not only for conductive materials, but also for non-conductive ones, such as glass panels, fibre cloth etc. Inspired by the electrostatic chucks used in industry, some researchers have attempted to apply electrostatic adhesion technology to wall climbing robots in recent years [9, 10]. Various kinds of wall climbing robots based on electrostatic adhesion technology have been implemented, which can climb on different wall surfaces, such as steel panels, wood, glass, concrete etc. However, all of the existing robots can only achieve simple forward and backward movements but cannot make a turn. In addition, there is little work about the electrostatic adhesion force calculation, due to the lack of an adhesion model and calculation method, which makes robot design and control very inconvenient.

In this paper, a wall climbing robot prototype based on electrostatic adhesion will be reported. Meanwhile, the modelling and calculation of the electrostatic adhesion force is discussed in detail. The remainder of this paper is organized as follows: Section 2 describes the robot system design, including electrode panel design, mechanical structure design of the robot, power supply system and control system design. In Section 3, the adhesion model is built and a formula for adhesion force calculation is deduced. Analysis of several important factors influencing the electrostatic adhesion force is conducted in Section 4. Experiments on the adhesion performance of the actual electrode panel and the climbing performance of the robot on various wall materials are carried out in Section 5. Finally, the conclusion of this paper is given in Section 6.

2. Robot System Design

2.1 Electrode Panel Design

The electrode panel is a key part of the robot system, for it not only plays the role of generating electrostatic adhesion force, but also is the travelling mechanism of the robot. In order to produce electrostatic adhesion force, the electrode panel typically comprises at least two sets of independent electrodes at different potentials. However, previous research indicates that ordinary bipolar electrodes will need a long time to get sufficient adhesion force, especially when the wall materials are dielectric. To improve electrostatic adhesion performance, such as the maximal attainable adhesion force and the excitation
speed of the adhesion force, we choose to use interdigital electrodes that have many boundaries [11]. It can be observed that the electric field in the vicinity of the boundary of the electrodes is relatively stronger than that far away from the boundary and this implies that the collection of induced and polarization charges occurs more quickly in the vicinity of the boundary. Hence, it is advantageous to form many boundaries with different potentials in the electrode pattern, to reduce the excitation time of the electrostatic adhesion force. In addition, in the case of industrial electrostatic chucks, rigid electrode panels are used, since the objects to be held have flat and smooth surfaces. However, in the case of wall climbing robots, walls are not always smooth enough. If rigid electrode panels are used, the effective contact area for electrostatic adhesion force generation will be sharply reduced, which results in a smaller adhesion force. Therefore, flexible electrode panels are more popular for wall climbing robots.

Fig. 1 shows a flexible interdigital electrode panel. The base of the panel is polyimide film, 25 μm in thickness. The interdigital electrodes are made from a flexible printed circuit board by etching processes, which are then covered by a 25 μm thick polyimide film. The width of the electrode and the space between two neighbouring electrodes are both 1mm. The whole electrode panel is 300mm long and 240mm in width. Due to the good flexibility of copper electrodes and polyimide film, the whole electrode panel is quite flexible and can adapt to the wall surface perfectly.

2.2 Mechanical Structure Design of the Robot

The robot proposed in this paper is a double tracked wall climbing robot and the mechanical structure is shown in Fig. 2. Two flexible electrode panels not only are used to generate electrostatic adhesion force, but also play the role of being the travelling mechanism of the robot. The flexible electrode panels are set on the front and back scrolls, which are covered by silicon rubber to increase friction between the electrode panels and the scrolls. The back scrolls are driven by two DC motors, while the front scrolls make slave rotation synchronously. The front and back support frameworks are connected by a carbon-fibre rod and the connecting elements can slide along the rod to control the relative distance between the front support framework and the back one, so that the tracks can be tensioned all the time. Two electric rings are used to keep rolling electrical contact between the power supply system and the electrode panels when they rotate with the motors. Two tails are employed in this robot structure to improve the ability of anti-peeling of the robot.

2.3 Power Supply System and Control System Design

The power supply system is used to drive the two DC motors and excite the electrode panels for electrostatic adhesion force generation. A schematic of power supply to the robot and operation of the electrode panels is shown in Fig. 3. The robot is driven using two DC motors powered by three lithium batteries in series. The batteries also directly power the electrode panel through the use of a commercially available DC-DC high voltage converter, which can output several thousand volts.

![Figure 1. Flexible interdigital electrode panel](image1)

![Figure 2. Mechanical structure of the robot](image2)

![Figure 3. Schematic of power supply to the robot and operation of electrode panels](image3)

![Figure 4. A basic model that adequately describes the performance of the electrode panel](image4)
receiver then controls the two DC motors and ensures that they work smoothly. The robot can achieve forward and backward movements freely. In addition, through differential rotation of the two DC motors, the robot can make a turn with a certain turning radius.

3. Modelling and Calculation of Electrostatic Adhesion Force

3.1 Theoretical Model

As introduced in Section 2, a flexible interdigital electrode panel, which is situated on the robot, is used to generate electrostatic adhesion force between the wall and the robot. A basic model that adequately describes the performance of the electrode panel is depicted in Fig. 4 [12]. In this model, the electrode structure consists of a planar array of parallel bar electrodes whose uniform pitch and width are 2p and 2a. Alternate positive and negative potentials are applied to the electrodes. Given the roughness of the wall surface, a simplified thin air layer is taken into account between the electrode panel and the wall. As the length of the electrode is much larger than the width, the edge effect along the length direction can be ignored. In addition, the electric field along the length direction is uniform, so we can transform this 3D problem into a 2D one by taking the cross-section of the electrode panel into consideration. The electric field caused by the marginal area of electrodes is also ignored for simplification of the model.

Due to the periodicity of the electrode structure, we can choose one period as the research object, which is the region of $-p \leq x \leq p$, shown in Fig. 4. For positive and negative voltages of the same magnitude are exerted on the neighbouring electrodes, which are symmetrical in relation to the y-axis, the spatial potential of the electrodes is an even function related to the y-axis.

According to Maxwell stress tensor formulation, the electrostatic adhesion force $F$ on the wall generated by the electrode panel on the robot can be derived by integrating the Maxwell stress tensor $T$ over the enclosing surface $S$ [13]:

$$F = \frac{1}{5} T dA = \frac{1}{5} \int \left( E_x^2 - E_x^2 \right) dA \quad (1)$$

As the Maxwell stress tensor $T$ relates directly with the electric field strength $E$, the electric field strength $E$ at the wall surface will be deeply studied in the next section.

3.2 Potential and Electric Field

The electric field throughout the solution space can be readily calculated from the electric potential. The electric field $E$, generated by the potentials applied to the electrodes, can be expressed in terms of a potential function $V$ as:

$$E = -\nabla V \quad (2)$$

In each dielectric region, the potential is a solution of the Laplace equation, which, in an isotropic medium, assumes the form:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \quad (3)$$

The electric potentials applied to the electrodes impose a definite $x$ dependence on the potential function in the plane of $y = 0$. This field variation can be described as a series expansion of the potential function in terms of cosine functions. The functions $\cos(n \pi x / p)$ form a complete orthogonal set over the domain $0 < x < p$ for integral values of $n$. The functions:

$$\phi_{1n} = \exp(\pm n \pi x / p) \cos(n \pi x / p) \quad (4)$$

$$\phi_{2n} = \cosh(n \pi y / p) \cos(n \pi x / p) \quad (5)$$

$$\phi_{3n} = a + by \quad (6)$$

are solutions of the Laplace equation (3). Thus, the spatial potentials can be expressed as follows:

$$V_1 = a_0 + \sum_{n=1}^{\infty} a_n \exp(k_n (-y + h_3)) \cos(k_n x) \quad h_5 \leq y \leq (7)$$

$$V_2 = b_0 + c_0 y + \sum_{n=1}^{\infty} \left[ b_n \exp(-k_n y) + c_n \exp(k_n y) \right] \quad 0 \leq y \leq h_3 \quad (8)$$

$$V_3 = d_0 + m_0 y + \sum_{n=1}^{\infty} \left[ d_n \exp(-k_n y) + m_n \exp(k_n y) \right] \quad \cos(k_n x) \quad -h_1 \leq y \leq 0 \quad (9)$$

$$V_4 = p_0 + q_0 y + \sum_{n=1}^{\infty} \left[ p_n \exp(-k_n (y + h_1)) + q_n \exp(k_n (y + h_1)) \right] \quad \cos(k_n x) \quad -h_2 \leq y \leq -h_1 \quad (10)$$

$$V_5 = w_0 + \sum_{n=1}^{\infty} w_n \exp(k_n (y + h_2)) \cos(k_n x) \quad y \leq -h_2 \quad (11)$$

where $k_n = n \pi / p$, $h_1$, $h_2$, and $h_3$ indicate the distance between the surface of the dielectrics and the $x$-axis, as shown in Fig. 4.

The different functional forms of the series expansions in (7)-(11) are dictated by the boundary conditions. Since the potential cannot become infinite as $|y| \rightarrow +\infty$, the linear term in $y$ is absent from (7) and (11). For the same reason, only the exponential function, whose value decreases with increasing values of $|y|$, is permitted in the series.
expansions in (7) and (11). Since the thickness of the wall is usually exceedingly large compared with the dielectric layers, it won’t produce significant deviation when treating it as infinite for simplification.

3.2 Boundary Conditions

At the dielectric interface, boundary conditions for normal and tangential components can be written as:

\[
\frac{\partial V}{\partial y} \bigg|_{y=h} = \frac{\partial V}{\partial x} \bigg|_{y=h} = 0
\]

Equation (12) can be assured if \( V \) is continuous at the interface, hence we convert (12) to the following form:

\[
V_i = V_j \bigg|_{y=h}
\]

Equation (14) remains true at every interface, including the interface between the electrodes and the dielectric, while equation (13) is violated on the electrodes. As on the electrodes, the value of potential function (8) and (9) must amount to \( U_1 \) on negative electrodes and \( U_2 \) on positive electrodes. It is clear that the only remaining undetermined coefficient is \( w_n \) since \( a_n, b_n, c_n, d_n, m_n, p_n, \eta_n \) can all be expressed by \( w_n \) via equations (7)-(14).

As mentioned above, equation (13) holds in the gaps between electrodes, while on electrodes, potentials are constant \( U_1 \) on negative electrodes and \( U_2 \) on positive electrodes. This can be expressed in formulas as follows, at plane \( y = 0 \):

\[
\begin{align*}
V_2 &= V_3 = U_1, \quad 0 \leq x \leq a \\
\frac{\partial V_2}{\partial y} &= \frac{\partial V_3}{\partial y}, \quad a < x < p - a \\
V_2 &= V_3 = U_2, \quad p - a \leq x \leq p
\end{align*}
\]

In practice, \( U_1 \) and \( U_2 \) usually have the same magnitude but opposite sign and the width of the electrodes is equal to that of the space between them, so the potential function is odd symmetry about line \( x = p/2 \). Notice that equation (11) is in the form of a Fourier series. Therefore, according to the characteristics of the Fourier series, we can obtain \( w_n = 0 \) (\( n = 1, 2, 3... \)), then only \( w_{2n-1} \) (\( n = 1, 2, 3... \)) should be solved in this case. Here we use the point matching method [14] to deal with the boundary matching problem in the interface of \( y = 0 \) which means that we satisfy the boundary conditions only at a finite set of discrete points \( x = x_i \). The points can be chosen arbitrarily, but in our application are spaced equidistantly for convenience. The total number of the points is equal to the items of the series expansion, in order to provide as many equations as we have unknown coefficients \( w_n \). We can convert the form of (15) to:

\[
\begin{align*}
&d_n + \sum_{n=1}^{N-1} (d_n + m_n) \cos(k_n x_i) = U_1 \quad 0 \leq x_i \leq a \\
&\sum_{n=1}^{N-1} k_n (\varepsilon_1 (c_n - b_n) + \varepsilon_n (d_n - m_n) \cos(k_n x_i) = 0 \quad a < x_i < p / 2
\end{align*}
\]

Transform (16) into matrix form:

\[
A \cdot W = b \quad \text{and} \quad W = [w_0, w_1, w_2, ..., w_{N-1}]^T
\]

After the coefficient matrix \( A \) is obtained, inversion of the matrix \( A \) leads to the determination of the unknown coefficients via:

\[
W = A^{-1} b
\]

Equation (18) can be solved by computer, from which other series expansion coefficients can be calculated and thus the potential function follows from (7)-(11). The electric field vector follows from (2).

3.3 Electrostatic Adhesion Force

As mentioned above, the electric field is identical on the \( z \)-axis, and the wall thickness can be regarded as infinite in the negative direction on the \( y \)-axis. Hence, the attraction force acting on the lower surface of the wall is negligible, so the force acting on the whole wall material in a period is:

\[
F = 2 \times \frac{1}{2} \int_0^p \left( \int_{y=0}^{y=\pm h} E_y^2 - E_z^2 \right) dx = \int_0^p \left( \int_{y=0}^{y=\pm h} (E_y^2 + 2E_z^2) \right) dx
\]

In equation (19), \( h' \) and \( h'' \) denote above and below the interface and \( l \) represents the length of the electrode.

4. Analysis of Several Important Factors Influence Electrostatic Adhesion Force

The electrostatic adhesion force generated by the electrode panel above depends on many parameters, including the voltages exerted on the electrodes, the permittivity of the wall and the insulating film, the thickness of the air layer and the insulating film and the structural parameters of the electrodes. In addition, atmospheric humidity and the electric conductivity of the wall and insulating film can also influence the electrostatic adhesion force to some extent. In this section, several important factors, which influence electrostatic adhesion force tremendously, will be fully analysed by simulation work and the theoretical calculation method.
proposed in Section 3. The initial simulation and calculation conditions are: negative and positive voltages are \( \pm 1000 \) volts; permittivity of the wall \( ( \varepsilon_2) \) is 2.55; permittivity of the insulating film \( (\varepsilon_1,\varepsilon_3) \) is 3.4; thickness of the air layer and insulating film are \( 5 \mu m \) and \( 25 \mu m \) respectively; the width of the electrode and the space between neighbouring electrodes are both \( 1 \) mm; the area of the electrode panel is \( 300 \text{mm} \times 240 \text{mm} \). We discuss the variations of electrostatic adhesion force related to each factor by making other parameters at the initial values above.

4.1 Excitation Voltage

The influence of excitation voltage on electrostatic adhesion force is firstly analysed by keeping other parameters unchanged. As it shown in Fig. 5, the electrostatic adhesion force increases with the excitation force on the electrodes approximately in relation of quadric parabola. Hence, it is desirable to increase excitation voltage to obtain a large adhesion force. However, the excitation voltage should not increase infinitely as it may cause dielectric breakdown of the insulating film or the air layer, which will result in the adhesion failure of the whole electrode panel.

4.2 Permittivity of the Wall Material and the Insulating Film

Material properties of the wall and the insulating film are also important factors that influence electrostatic adhesion force. As the insulating film and the wall that robots usually work on are dielectric, we choose permittivity as the main parameter to discuss this problem. The influence of wall permittivity on adhesion force is shown in Fig. 6. It can be observed that the simulation data and the theoretical calculation data agree. As the wall permittivity varies from 2 to 10, the adhesion force increases from \( 1.7 \) N to \( 37 \) N. This remarkable influence can be explained because a wall with larger permittivity is easily polarized, so more polarization charges can be obtained, which results in a larger adhesion force. We may infer that if the wall material is a conductor, the adhesion force should be very large. Fig. 7 depicts the influence of insulating film permittivity on adhesion force. The simulation data are a little larger than the theoretical calculation data due to the inherent errors of the simulation tool and the calculation method, but as a whole, we realize that the influence of the insulating film on adhesion force is not obvious since the insulating film just plays the role of insulation protection.

4.3 Thickness of Air Layer

Due to roughness of the wall surface, the electrode panels cannot contact the wall completely, which results in the existence of an air layer between the electrode panels and the wall. To simplify the adhesion model, the thickness of the air layer is assumed to be uniform and have a value directly related to the roughness of the wall. The electrostatic adhesion force varies from \( 3.81 \) N to \( 2.92 \) N as the thickness of the air layer varies from \( 5 \mu m \) to \( 25 \mu m \), as is shown in Fig. 8. The results indicate that it is more difficult to get sufficient adhesion force on a rough wall. Therefore, we should improve the flexibility of the electrode panel to make it contact with the wall surface more closely so that a stronger electrostatic adhesion force can be expected. In addition, there may be a micro breakdown of the air layer between the insulating film and the wall if the electric field in the tiny space exceeds the minimum limit of the spark discharge, so we must bear in mind that the excitation voltage should not be too high.

4.4 Thickness of Insulating Film

The thickness of the insulating film cannot be too small to avoid the dielectric breakdown of it. On the other hand, it cannot be too large, since the electric field will be weakened as the thickness increases, which will decrease the electrostatic adhesion force generated by the electrode panels. Fig. 9 shows the electrostatic adhesion force for a thickness of insulating film variation from \( 15 \mu m \) to \( 55 \mu m \). The small discrepancy between the simulation data and the theoretical calculation data is due to the inherent errors of the simulation tool and the calculation method. It can be observed that, to obtain stronger adhesion force, a smaller thickness of insulating film is preferable, under the precondition of avoiding dielectric breakdown of the insulating film.

4.5 Structural Parameters of the Electrode

As mentioned in section 2, it is advantageous to form many boundaries to increase the maximum attainable force and the excitation speed of the adhesion force. However, excessive increase of the boundaries will lead to a likewise decrease in the total area of the electrodes, resulting in a decrease of the amount of polarization charges. The electrode width and the space between neighbouring electrodes are two key parameters for the electrostatic adhesion force, so there must be optimal values for an electrode panel with certain area. Firstly, by keeping the space between neighbouring electrodes at \( 1 \) mm, we analyse the influence of electrode width on adhesion force (the result is shown in Fig. 10). As the electrode width increases, the adhesion force decreases, since the amount of boundaries decreases accordingly. Usually, we can determine the space between neighbouring electrodes according to electric breakdown condition first. Then an electrode width as small as possible is desirable to get a large adhesion force. Next, by keeping the electrode width at \( 1 \) mm, the influence of the space between neighbouring electrodes is investigated (Fig. 11 shows the result). The adhesion force varies from \( 6.94 \) N to \( 0.85 \) N as the space between
neighbouring electrodes varies from 0.5mm to 2.5mm. This implies that we need to decrease the space in order to get a larger adhesion force. However, we still need to bear in mind that the space between neighbouring electrodes cannot be too small in case of electric breakdown.

**Figure 5.** Excitation voltage influence on adhesion force

**Figure 6.** Wall permittivity influence on adhesion force

**Figure 7.** Insulating film permittivity influence on adhesion force

**Figure 8.** Thickness of air layer influence on adhesion force

**Figure 9.** Thickness of insulating film influence on adhesion force

**Figure 10.** Width of electrode influence on adhesion force
5. Experiments

5.1 Adhesion Performance of the Electrode Panel

The adhesion performance of the electrode panel is crucial to the robot design, which can deeply affect the climbing performance of the robot. Therefore, experiments into the adhesion performance of the electrode panel were carried out on three common material surfaces, which are board, drywall and glass, as is shown in Fig. 12. To evaluate the performance, we measured the holding force in a parallel direction to the wall surface, instead of the electrostatic adhesion force in a vertical direction to the wall surface for ease of measurements. For evaluation, force was applied on a pothook, which was fixed on the electrode panel. We increased the force gradually until the electrode panel slipped against the wall surface. Then the maximum force was recorded as the holding force. The experiment data are given in Fig. 13. The force on glass is larger than that on board and wall since the permittivity of glass is larger and the surface of the glass is smoother. In addition, we realize that the experiment data are larger than the simulation data and theoretical calculation data proposed before, due to the influence of negative air pressure force in the experiment.

5.2 Climbing Performance of the Robot on Various Wall Materials

We tested the climbing performance of the robot prototype on various wall surfaces. The experiment results are satisfactory, which verifies the feasibility of electrostatic adhesion technology for wall climbing robots and the rationality of the theoretical model and computation method proposed in this paper. The robot can achieve forward and backward movements freely on different wall surfaces, meanwhile, it can also turn on the wall with a turning radius that is not too small. The movement performances on different wall surfaces are shown in Fig. 14 and the main performance parameters of the robot prototype are given in Table 1.

![Figure 12. Electrode panel adhered on wall surface](image)

![Figure 13. Holding forces on different wall surfaces](image)

![Figure 14. Robot climbing on board surfaces](image)

| Parameter                  | Value             |
|----------------------------|-------------------|
| Self-weight                | 700g              |
| size                       | 360mm * 360mm     |
| velocity                   | 0.2mm/s           |
| turning radius             | ≥ 0.5m            |
| power supply voltage       | 12V               |
| adhesion voltage           | 3000V             |
| maximum holding force      | 20N               |
| power consumption          | 3W                |

Table 1. Main performance parameters of the robot prototype

6. Conclusion

Electrostatic adhesion offers advantages over other types of technologies for wall climbing robots, including high adaptability and a wide applied range on various wall surfaces.
surfaces, simple structure which benefits the integration, miniaturization and lightness of the robot and low power consumption. A wall climbing robot using electrostatic adhesion force generated by flexible interdigital electrodes has been described in this paper. This robot is a double tracked wall climbing robot with two electrode panels as the adhesion mechanism and travelling mechanism simultaneously. Climbing performances of the robot on various wall materials are also tested by experiments, which verify the feasibility of electrostatic adhesion technology for wall climbing robots.

Modelling and calculation of electrostatic adhesion force is crucial for wall climbing robot design. An analytical model of the electrostatic adhesion field and force between the wall and the electrode panel has been established and verified by FEM simulation and experimental work. The potential function is expressed by series expansions in terms of solutions of the Laplace function. The expansion coefficients of different series are related to each other and the potentials applied to the electrodes via boundary conditions. Based on this model, the electrostatic adhesion force is calculated using the Maxwell stress tensor formulation. Furthermore, several important factors which influence the electrostatic adhesion force are analysed and discussed in detail and the experiments on the adhesion performance of the electrode panel and climbing performance of the robot on various wall materials are also carried out. The model and analysis given in this paper show good agreement and could be used to guide robot design based on electrostatic adhesion technology.

Further study is required to establish a dynamic adhesion force model considering the movement of the electrode panel on the robot, especially when the robot is turning. Another area of investigation for the future will be focused on the mathematical modelling of the surface roughness, instead of the simplified uniform air layer in this paper. In addition, the adaptive control of the wall climbing robot based on electrostatic adhesion technology is also an interesting problem.

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