Design and simulation of magnetic adsorption System for 3D curved surface mobile Robot

Jing Hu\textsuperscript{1,a}, Jing Ren\textsuperscript{2,b}, Guomin Liao\textsuperscript{3,c}, Guichuan Hu\textsuperscript{2,d}\textsuperscript{*}

\textsuperscript{1}School of Intelligent Manufacturing, Chongqing College of Architecture and Technology, Chongqing, China
\textsuperscript{2}School of mechanical and power engineering, Chongqing University of science and technology, Chongqing, China
\textsuperscript{3}School of Digital Engineering, Chongqing College of Architecture and Technology, Chongqing, China
\textsuperscript{a}email: 278252640@qq.com, \textsuperscript{b}email: 1031650081@qq.com, \textsuperscript{c}email: 1643493318@qq.com, \textsuperscript{d}email: huguichuan@cqust.edu.cn

Abstract: With the deepening of intelligent manufacturing applications, 3D curved surface mobile robots need to be developed to meet more and more practical engineering requirements. And the adsorption system is the key part of 3D curved surface mobile robot to overcome the gravity of the robot itself. Firstly, the relationship between adsorption force and inclination angle was calculated on the basis of mechanical characteristics. Secondly, we simulated the magnetic adsorption situation and acquired the relation curves of the adsorption force. Finally, the structure size and adjustment scheme of the magnetic adsorption system were determined according to the simulation results.

1. Introduction
Mobile robot is an integrated system integrating environment perception, dynamic decision-making and planning, behavior control and execution. With the deepening of intelligent manufacturing applications, the application scenarios of mobile robots are also expanding. Traditional planar mobile robots are difficult to meet the requirements of large ships, integrated pipe corridors, wind turbine blades and other curved working environments. Therefore, 3D curved surface mobile robots need to be developed to meet more and more practical engineering requirements.

The largest difference between 3D curved surface mobile robot and planar mobile robot is that it needs adsorption force to overcome the gravity of the robot itself, so the adsorption system is the key part of 3D curved surface mobile robot. Magnetic adsorption is one of the common adsorption methods, especially suitable for metal surface\cite{1}. In this paper, the magnetic adsorption system of 3D curved surface mobile robot was designed and simulated.

2. Analysis of mechanical properties

2.1 Structure and working principle
On the basis of the overall design of the robot\cite{2}, the mechanical characteristics were analyzed. The structure of the robot body is shown in Figure 1(a), the robot mainly included several parts: control
module, driving system, magnetic adsorption system, visual inspection system and connection frame.

![Diagram of robot body and adsorption regulating device](image)

The magnetic regulating adsorption regulating device is shown in Figure 1(b), the distance between the magnet and the working surface was automatically adjusted by the electromotor and the screw, and the adsorption force changed accordingly. In addition, the on the caterpillar band also had a certain adsorption force, and the sum of these forces was the total force of the robot.

### 2.2 Analysis of adsorption force

When the robot moves on the three-dimensional surface, it is easy to fall off, slip and other dangerous phenomena. In order to ensure the stability of adsorption, the limit conditions of sliding critical point and overturning critical point were analyzed\(^3\). As the robot was symmetrical, the unilateral mechanical model of the robot was established to simplify the calculation, as shown in Figure 2.

![Unilateral mechanical model of the robot](image)

In order to keep the robot from sliding down, the adsorption force needs to work against gravity and load. The force inequation was as follows:

\[
\begin{align*}
\mu_i \sum_{i=1}^{n} N_i &\geq G_x \\
\sum_{i=1}^{n} F_{ma} + F_{ma} - \sum_{i=1}^{n} N_i - G_y = 0
\end{align*}
\]

In the Equation (1), \( \mu_i = 0.65 \) which is the coefficient of friction, \( N_i \) is the supporting force of a
single adsorption unit, \( G = 125N \) which is half the gravity and load, \( G_x \) is the component of \( G \) along the X-axis, \( G_y \) is the component of \( G \) along the Y-axis, \( \alpha \) is the surface inclination angle and \( 0^\circ \leq \alpha \leq 90^\circ \), \( i \) is the number of adsorption unit, \( n \) is the number of adsorption units in contact with the surface, \( F_{ma} \) is the adsorption force of a single adsorption unit, \( F_m \) is the adsorption force of magnetic adsorption regulating device.

The solution of the Inequation (1) was as follows:

\[
8F_{mi} + F_{ma} \geq 192.3\cos \alpha + 125\sin \alpha
\]  \hspace{1cm} (2)

As shown in Figure 2, when the robot is adsorbed on the surface, \( G \) tends to make it overturn. In the process of overturning, the robot first falls off at point B, and then rotates around point A. The moment balance equation with point A was as follows:

\[
F_{ma}l - \frac{1}{2}F_{ma} - N_i l - \frac{1}{2}G_y - HG_x = 0
\]  \hspace{1cm} (3)

In the Equation (3), \( l \) is the contact length between the adsorption unit and the surface, in this case \( l = 160mm \). \( H \) is the distance from the robot's center of mass to the surface, in this case \( H = 60mm \).

The condition that the robot does not overturn is \( N_i \geq 0 \), hence, the solution of the Equation (3) was as follows:

\[
2F_{mi} + F_{ma} \geq 93.75\cos \alpha + 125\sin \alpha
\]  \hspace{1cm} (4)

Taking the Inequation (2) and Inequation (4) into the inequation set, the relationship between the adsorption force and the inclination Angle was as follows:

\[
\begin{cases}
8F_{mi} + F_{ma} \geq 192.3\cos \alpha + 125\sin \alpha \\
2F_{mi} + F_{ma} \geq 93.75\cos \alpha + 125\sin \alpha
\end{cases}
\]  \hspace{1cm} (5)

The adsorption force \( (F_m) \) satisfied the following equation:

\[
F_m = F_{ma} + F_{ma}
\]  \hspace{1cm} (6)

Assuming Equation (6), the solution of Inequation set (5) as follows:

\[
F_m \geq 77.325\cos \alpha + 125\sin \alpha
\]  \hspace{1cm} (7)

3. Simulation and optimization of magnetic adsorption system

ANSYS Maxwell is an electromagnetic field analysis tool for the development of electromechanical products[4]. In this paper, ANSYS Maxwell was used to simulate the magnetic adsorption situation and optimize the parameters.

3.1 Magnetic adsorption unit

The structure diagram of magnetic adsorption unit as shown in Figure 3(a), and the factors affecting the adsorption force of magnetic adsorption unit include: the length of magnet \( (L) \), the width of magnet \( (W) \), the height of magnet \( (H_1) \), the height of the magnetic yoke \( (H_0) \) and the interval between the adsorption unit and the surface \( (S) \). Among them, \( L, \ W \) and \( H_0 \) are the basic parameters of the robot, which are generally not suitable for change, so the two parameters \( S \) and \( H_1 \) were mainly optimized.
(1) Take the $H_1$ as a variable
The height of magnet ($H_1$) was from 2 to 10mm, and other structural parameters of the magnetic adsorption unit were $W = 10$mm, $H_0 = 4$mm, $L = 40$mm, $S = 3$mm. The simulation was carried out with a step size of 1mm, and the relationship between the height of magnet ($H_1$) and the adsorption force of a single adsorption unit ($F_{mi}$) is shown in Figure 4. As a result, the $F_{mi}$ was proportional to $H_1$.

(2) Take the $S$ as a variable
The interval between the adsorption unit and the surface ($S$) was from 1 to 20mm, and other structural parameters of the magnetic adsorption unit were $W = 10$mm, $H_0 = 4$mm, $H_1 = 5$mm $L = 40$mm. The simulation was carried out with a step size of 2mm, and the relationship between the interval between the adsorption unit and the surface ($S$) and the adsorption force of a single adsorption unit ($F_{mi}$) is shown in Figure 5. As a result, the $F_{mi}$ was inversely proportional to $S$. 

![Figure 3 The arrangement and size of magnets](image)

![Figure 4 The relationship between $H_1$ and $F_{mi}$](image)
3.2 Magnetic adsorption regulating device

The arrangement of magnets on the mounting plate is closely related to the magnetic energy utilization rate of the device. When the magnets are arranged in a cross with different poles, the magnetic energy utilization rate is higher\(^5\). Hence, the arrangement and size of magnets is shown in Figure 3(b).

When the magnet arrangement was constant, the adsorption force of magnetic adsorption regulating device \(F_{ms}\) was related to the height of magnet \(H_2\) and the interval between magnet to surface \(S\).

(1) Take the \(H_2\) as a variable

The height of magnet \(H_2\) was from 1 to 10mm, and the interval between magnet to surface \(S\) was 6mm. The simulation was carried out with a step size of 1mm, and the relationship between the height of magnet \(H_2\) and the adsorption force of magnetic adsorption regulating device \(F_{ms}\) is shown in Figure 6. As a result, the \(F_{ms}\) was proportional to \(H_2\).

(2) Take the \(S\) as a variable

The interval between magnet to surface \(S\) was from 1 to 30mm, and the height of magnet \(H_2\) was 4mm. The simulation was carried out with a step size of 2mm, and the relationship between the interval between magnet to surface \(S\) and the adsorption force of magnetic adsorption regulating device \(F_{ms}\) is shown in Figure 7. As a result, the \(F_{ms}\) was inversely proportional to \(S\).
6

3.3 Magnetic adsorption structure size

In order to make the robot work properly, the adsorption force of the magnetic adsorption system should meet the Inequality (7). The magnetic adsorption force \( F_m \) varied with the surface inclination angle \( (\alpha) \), meanwhile, in the Equality (6), \( F_m \) was consisted of a fixed force \( F_{mi} \) and an adjustable force \( F_{ms} \).

1) Structure size of magnetic adsorption unit

The main parameters of the magnetic adsorption unit is shown in Table 1.

![Figure 7 The relationship between S and Fms](image)

| Parameters                  | Value       | Parameters                  | Value       |
|-----------------------------|-------------|-----------------------------|-------------|
| Length of magnet \((L)\)    | 40mm        | Width of magnet \((W)\)     | 10mm        |
| Height of magnet \((H_1)\)  | 5mm         | Height of the magnetic yoke \((H_0)\) | 4mm        |
| Interval between unit and surface \((S)\) | 3mm         |                             |             |

Among them, \( L, W \) and \( H_0 \) were the basic structural parameters of the robot. As shown in Figure 5, the \( F_{ms} \) was proportional to \( H_1 \). But when \( H \geq 5\text{mm} \), the incremental curve was slow down, at the same time in order to reduce the mass of the adsorption unit and combine with the size of magnets on the market, so the \( H_1 = 5\text{mm} \) was selected. As shown in Figure 6, the \( F_{ms} \) was inversely proportional to \( S \). Selecting a smaller \( S \) to increase the adsorption force \( F_{ms} \) at the same time combined with the thickness of the encapsulation rubber, so the \( S = 3\text{mm} \) was selected. According to these parameters, \( F_{ms} = 71.874\text{N} \) was calculated by ANSYS Maxwell.

2) Structure size of magnetic adsorption regulating device

Substituting \( F_{ms} = 71.874\text{N} \) and Equation (6) into Inequation (7), the adsorption force of magnetic adsorption regulating device was as follows:

\[
F_{ms} \geq 154.65\cos\alpha + 250\sin\alpha - 143.75 \tag{8}
\]

In the equation (8), \( \alpha \) is the surface inclination angle and \( 0^\circ \leq \alpha \leq 90^\circ \). The relationship between the adsorption force \( (F_{ms}) \) and the inclination angle \( (\alpha) \) is shown in Table 2, and the relation curve is shown in Figure 8.

| Inclination angle \((\alpha)\) | 0  | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|------------------------------|----|----|----|----|----|----|----|----|----|----|
| Adsorption force \((F_{ms})\) | 14.65 | 35.85 | 55.71 | 74.09 | 90.83 | 105.82 | 118.93 | 130.08 | 139.16 | 146.13 |
| Inclination angle \((\alpha)\) | 50  | 55  | 60  | 65  | 70  | 75  | 80  | 85  | 90  |
| Adsorption force \((F_{ms})\) | 150.91 | 153.49 | 153.83 | 151.93 | 147.82 | 141.51 | 133.06 | 122.53 | 110 |
Figure 8 The relationship between $F_{ms}$ and $\alpha$

For the changing adsorption force ($F_{ms}$), adjusting the interval between the adsorption unit and the surface ($S$) to meet the requirements. Extracting the table in Figure 8 and comparing it with Table 2, the adjustment scheme of the interval is shown in Table 3.

| Inclination angle $\alpha$ (°) | 0~10 | 10~15 | 15~20 | 20~30 | 30~80 | 80~90 |
|-------------------------------|------|------|------|------|------|------|
| Interval $S$ (mm)             | 12   | 11   | 10   | 9    | 8    | 9    |

4. Conclusion

(1) On the basis of the overall design of the robot, the mechanical characteristics were analyzed and the relationship between adsorption force and inclination angle was calculated.

(2) We simulated the magnetic adsorption situation by ANSYS Maxwell, and acquired the relationship curves of the adsorption force.

(3) According to the simulation results, the structure size and adjustment scheme of the magnetic adsorption system were determined.

Acknowledgments

This paper is from the science and technology research project of Chongqing Education Commission, Research on cable health of cable-stayed bridge based on intelligent inspection robot (KJQN201905203).

Reference

[1] Guo Ganggang. Research on Adaptive Permanent Magnetic Adsorption Wall Climbing Robot Technology[D]. Northeast Petroleum University. 2020.6

[2] Hu Jing, Ren Jing. Structure design of Large Francis turbine runner blade defect detection robot[C]. Proceedings of ICPECA 2021, China, IEEE: 2021:944-947.

[3] Xiong Diao, Liu Yuliang. Research on Force Analysis and Stability Simulation of crawler Wall climbing Robot[J]. Journal of Mechanical and Electrical Engineering, 2015, 32 (7): 929-932.

[4] Liu Huijuan. Ansys Maxwell 13 Example analysis of electric motor electromagnetic field[M]. Beijing, National Defense Industry Press, 2014.

[5] Zhao Jiankun, Ye Jiawei. Design optimization of permanent magnet adsorption unit based on finite element analysis[J]. Mechanical design and manufacture, 2019(3):47-49.