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Design and motion control analysis of double helix wall climbing robot

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Abstract:
For the detection environment of complex walls such as high-rise buildings, a double helix wall climbing robot (DHWCR) with strong adsorption force and good stability is designed and developed, which uses symmetrical propellers to provide adsorption force. The symmetrical driving structure can provide smooth thrust for the DHWCR, so that the robot can be absorbed to the wall surface with different roughness. A left and right control frame with multiple degrees of freedom is designed, which can adjust the fixed position of the brushless propeller motor in the front and back directions, realize the continuous adjustable thrust direction of the robot, and improve the flexibility of the robot movement. Using the front wheel steering mechanism with universal joint, the steering control of the DHWCR is realized by differential control. In the vertical to ground transition, the front and rear brushless motors can provide the pull up and oblique thrust, so that the DHWCR can smoothly transition to the vertical wall. The motion performance and adaptability of the DHWCR in the horizontal ground and vertical wall environment are tested. The results show that the DHWCR can switch motion between the horizontal ground and vertical wall, and can stably adsorb on the vertical wall with flexible attitude control. The DHWCR can move at a fast speed. The speed on the horizontal ground is higher than that on the vertical wall, which verifies the feasibility and reliability of the DHWCR moving stably on the vertical wall.
Keywords: *Double helix; Wall climbing robot; Reverse thrust adsorption; Structural design; Motion control*

Introduction

Recently, skyscrapers have become an indispensable part of modern cities. While high-rise buildings bring benefits to people, they also bring many problems, such as the cleaning, quality monitoring and maintenance of the exterior wall of high-rise buildings. Wall climbing robots (WCRs) can replace human beings to complete many extreme tasks [1-2]. By integrating ground mobile robots with climbing adsorption technology, they can efficiently operate in vertical altitude [3-4]. The research area of WCRs has steadily gained interest over the years as a promising approach to remote inspection and maintenance of big and hard to reach spaces. At present, WCRs are mainly applied in industries, railways, oil tanks, shipping, fire departments and reconnaissance activities, and can replace human beings to perform building deconsolization, glass exterior wall cleaning, aerial circuit maintenance, anti-terrorism reconnaissance and hull detection [5-8].

Many different approaches have been proposed for the WCRs' adhesion including magnetic, pneumatic, mechanical and material-based methods, and their locomotion including leg and wheel-based, sliding frames and sequential robotic structures. According to the adsorption method, the WCR can be divided into magnetic adsorption, bionic, vacuum adsorption, and reverse thrust [9-12]. According to the movement mode, it can be divided into wheel, crawler, foot, and wheel-foot compound movement.

The magnetic adsorption WCR can be applied only in the ferrous medium of the structure. This kind of robot can be further subdivided into two adsorption forms, namely permanent magnet adsorption and electromagnetic adsorption, both of which have their own advantages. At present, permanent magnet adsorption is more widely used [13-14]. Magnetic adsorption WCR through magnetic material adsorption to the wall surface, complete the wall cleaning task. However, it is only applicable to the wall surface of magnetic materials with poor adaptability, so it is mainly used to detect the inner

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and outer surfaces of large metal buildings. Magnetic adhesion methods can be applied only in the ferrous medium of the structure; however, pneumatic adhesion methods are well suited in WCRs for glass curtain wall and other structures.

Bionic robots are WCRs that imitate the characteristics of animal feet or pastes. This kind of bionic robot using adhesive material has the characteristics of complex drive control and fuzzy hook, so its application scope is relatively narrow. The robot is highly adaptable to the wall surface, but the cost is high. According to different adsorption methods, it can be divided into dry adhesion and wet adhesion [15-17]. However, at present, the technology of bionic WCR is immature, and the load capacity of robot is not strong. The vacuum adsorption WCR is the earliest robot, which is divided into active vacuum and passive vacuum. The active vacuum depends on the vacuum generator/pump and other accessories, and the passive vacuum is created by pressing the suction cups without using any electric power [18].

It is seen from these developed adsorption methods that reverse thrust is the most used and suitable technique for developing WCRs. RTAWCR is a kind of robot that uses screw pumps or ducted fans to generate appropriate thrust to achieve wall adsorption [19]. This force is relatively stable, and the robot can be reliably adsorbed on the wall. Since the generating device does not touch the wall, the robot does not have high requirements for the roughness of the wall. The thrust can be controlled simply by the switch of the wings. Desorption can be achieved when the power supply stops.

By comprehensive analysis of the above types of WCRs, it can be seen that although existing WCRs have wall-climbing functions, they generally have problems such as unstable adsorption, low stability, poor obstacle climbing ability, great potential safety hazards and low walking efficiency. And part of the bionic foot is expensive, there are restrictions on all aspects of the wall requirements.

To solve the above problems, this paper designs a double helix wall-climbing robot (DHWCR) with strong adsorption force and good stability, which can move on the horizontal ground and vertical wall. The propeller head and the front wheel steering mechanism can make the DHWCR flexibly switch between the horizontal ground and the corner surface. The DHWCR can climb up, down and turn on the 90° wall, while exploring the surrounding environment. Under the condition that the DHWCR can absorb effectively, the multi-directional turning drive control is realized. The speed test experiments are carried out on the horizontal ground and the vertical wall. The results show that the DHWCR can switch freely between the horizontal ground and the vertical wall, and can stably adsorb on the vertical wall with stable attitude control. The moving speed on the horizontal ground is higher than that on the vertical wall. The flexible driving control has laid a foundation for the obstacle crossing, detection and inspection of the DHWCR when moving on the wall.

1 Overall design of DHWCR adsorption drive control

In order to make the DHWCR complete its work in various environments, it is necessary to ensure the overall stability of the robot as far as possible during the climbing process. The DHWCR should be as lightweight as possible, so that the robot can be more stable adsorption on the wall. The overall design of the DHWCR system includes two parts: hardware and software design. Figure 1 shows the overall control design scheme.

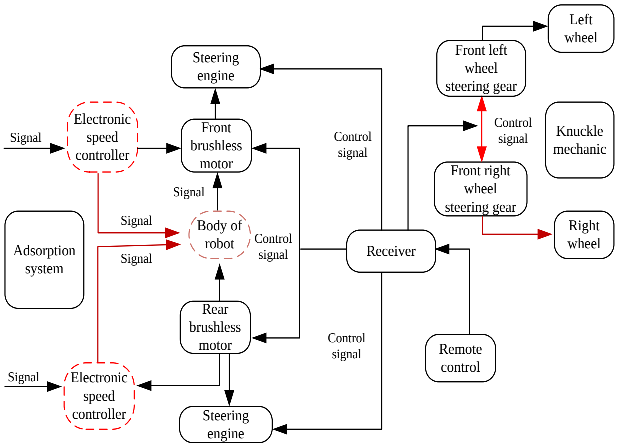


Figure 1 Overall control design of DHWCR

The overall structure of the DHWCR is shown in Figure 2, including the propeller head, brushless motor module, front wheel steering mechanism module, propeller steering gear control template and wireless handle control module. The motion control of the DHWCR and the brushless motor can be adjusted according to the steering gear. The DHWCR has low requirements on the wall, which can ensure the stable adsorption on the wall surface, and has a certain load capacity. At the same time, the reverse thrust can be adjusted by changing the motor control signal.

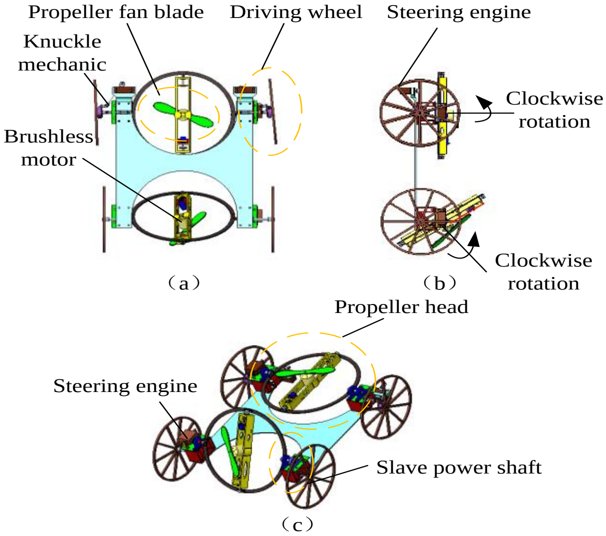


Figure 2 Three-dimensional diagram of the overall structure of a DHWCR

2 Structure design and motion control of DHWCR

2.1 Propeller head

In order to realize the stable adsorption motion of the DHWCR, the design of the head should be able to adjust the angle between the propeller and the climbing wall. As shown in Figure 3, the gimbal fixing device includes steering gear, brushless motor, bearing, power rod and outer ring. In the adsorption movement, the direction of the tension can be adjusted by controlling the steering gear through the controller. The head structure has multiple degrees of freedom and can adapt to different types of concave and convex wall adsorption. Due to the simultaneous operation of two brushless motors, the front and rear directions can be adjusted arbitrarily, which improves the climbing efficiency and the stability of adsorption.

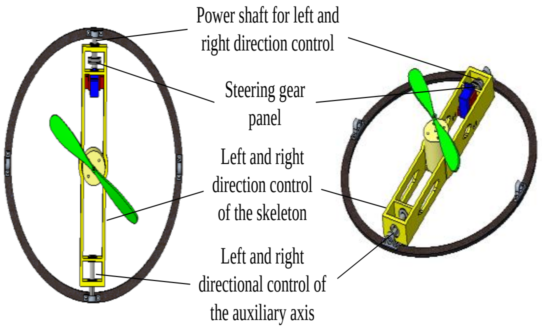


Figure 3 Design of propeller head

2.2 Front wheel steering mechanism

The steering mechanism module of the DHWCR includes universal joint, steering gear, connecting rod, etc. Signals can be sent to the Arduino control board through the controller to realize the control of the steering gear. Steering mechanism module has a steering gear on the left and right sides, through the connecting rod to drive the hub to achieve steering. The steering mechanism module is connected by multiple universal joints, which is light in weight and has high turning efficiency. It can realize fast turning on the horizontal and vertical walls and has high stability. Figure 4 shows the three-dimensional diagram of the front wheel steering mechanism module.

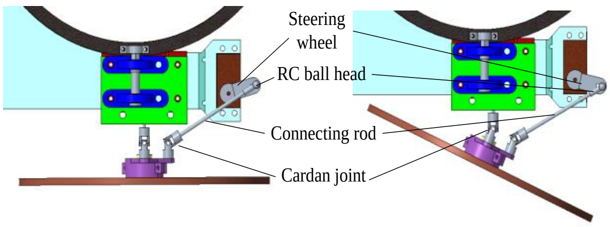


Figure 4 Front wheel steering mechanism module diagram

2.3 The linear motion of the DHWCR

The overall motion of the DHWCR can be divided into two parts: the straight motion on the wall and the straight motion on the ground. When moving in a straight line on the ground, the front and rear propellers form the same included angle with the ground, the brushless motor rotates at a high speed, and the air inside the paddle flows at different speeds from the air outside, generating a tension. Due to the different included angle with the ground, the tension finally pushes the DHWCR forward at different speeds, as shown in Figure 5.

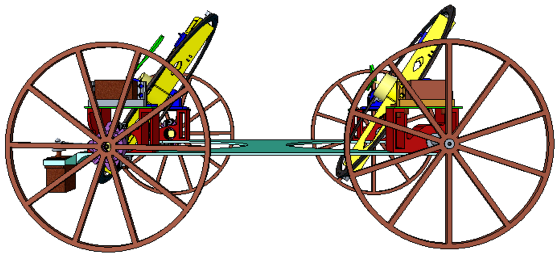


Figure 5 3D diagram of horizontal ground motion of DHWCR

When the DHWCR works on a vertical wall, it needs to overcome its own gravity, so in order to keep the robot crawling on the vertical plane, it needs to generate a slanting downward thrust, and in the direction of the reaction force with the wall, it will generate a tension opposite to gravity. The designed propeller head has multiple degrees of freedom, which can realize 180° rotation in four directions, as shown in Figure 6. The design of the double helix head can ensure that when the wall roughness and wall angle change, it can still adjust the speed and angle of the double brushless motor, adjust the tension, to ensure the stable movement of the DHWCR.

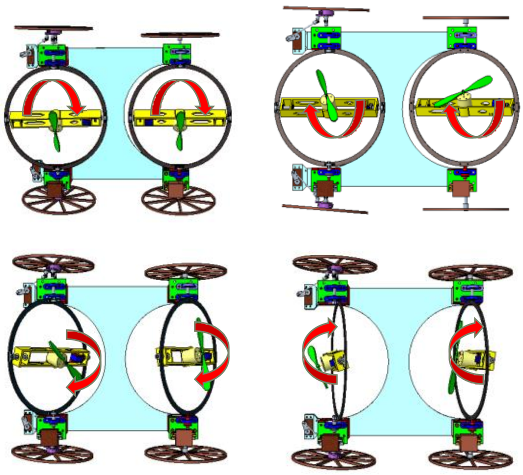


Figure 6 Schematic diagram of front, rear, left and right propeller head rotation

2.4 The steering motion of the DHWCR

In order to achieve smooth steering motion, the steering mechanism includes universal joint, steering gear, connecting rod and chuck. The controller sends signals and transmits them to the steering gear for control. The DHWCR is installed with two steering gear. When the steering gear rotates to different positions, the hub angle connected by connecting rod also rotates accordingly, which can realize smooth steering from left to right. The left and right sides of the steering mechanism use six universal joints on each side, which is light in weight and high in turning efficiency. When moving on the plane and vertical walls, there will be no side component force. Figure 7 shows the turning diagram of the DHWCR.

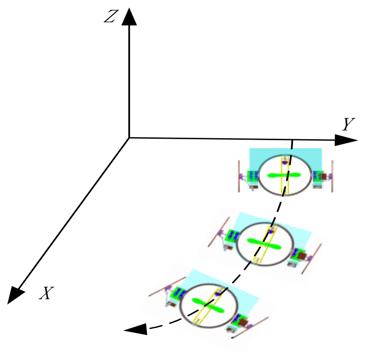


Figure 7 Steering diagram of the DHWCR

3 Structure design and motion control of DHWCR

3.1 The program design of propeller steering control module

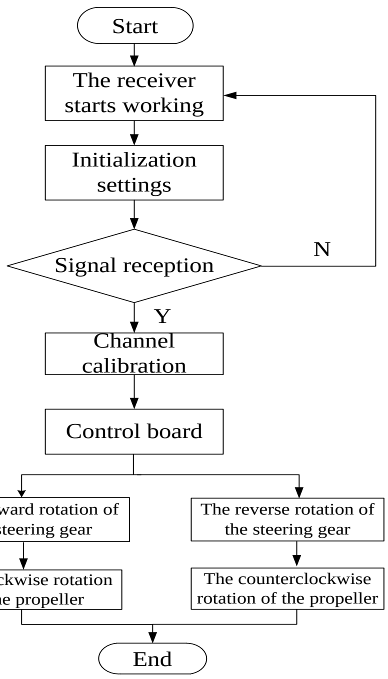


Figure 8 The flow chart of propeller steering machine control module program design

After receiving the signal through the receiver, the DHWCR controls the steering gear, and drives the bearing and brushless motor to control the rotation of the frame. When the brushless motor is working, it will produce downward tension in different directions. The receiver has a multi-channel control mode. The propeller steering machine is connected with different channels, which can realize the separate transmission of two signals. The direction of the fixed position of the front brushless motor and the direction of the fixed position of the rear brushless motor can be controlled respectively. The flow chart of propeller steering machine control module program design is shown in Figure 8.

3.2 Program design of front wheel steering mechanism module

After receiving the signal, the steering gear controlling the front wheel steering mechanism drives the connecting rod to make the hub turn around. Part of the control procedure is as follows.

```
SoftwareSerial softSerial(4, 2); //rxt    txt
char cmdChar = '5';
char cmdCharSave = cmdChar;
void setup() {
myservo1.attach(9);
   myservo2.attach(6);
   softSerial.begin(9600);
   delay(100);
   Serial.begin(9600);
   delay(100);
   myRadio.begin();
   myRadio.setChannel(115);
   myRadio.setPALevel(RF24_PA_MAX);
   myRadio.setDataRate( RF24_250KBPS );
myRadio.openReadingPipe(1,addresses[0]);
   myRadio.startListening();}
Servo myservo1;
Servo myservo2;
int i = 0;
void youzhuan()
{
  for (i = 0; i < 90; i++)
{
myservo1.write(i);
myservo2.write(i);
delay(10);
}
}
void zuozhuan()
{
for (i = 90; i >= 0; i--) { //  从 90 到 0 °
myservo1.write(i);
myservo2.write(i);
   delay(10);
}
}
```

3.3 Program design of brushless motor module

The receiving controller can adjust the speed of the propeller brushless motor and transmit the control signal to the DHWCR. For different wall surface, the tension can be adjusted, the front and rear brushless motor work at the same time. When moving from the horizontal ground to the vertical wall, the brushless motor generates upward tension. The brushless motor controls the frame to rotate to a certain angle, and pushes the DHWCR to realize the transition from plane to vertical. The software design flow chart of brushless motor module is shown in Figure 9.

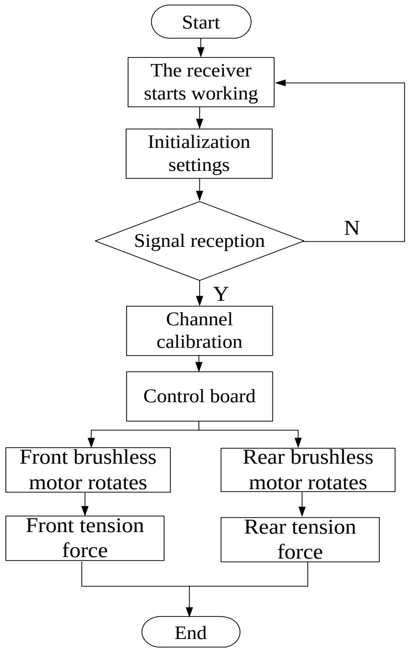
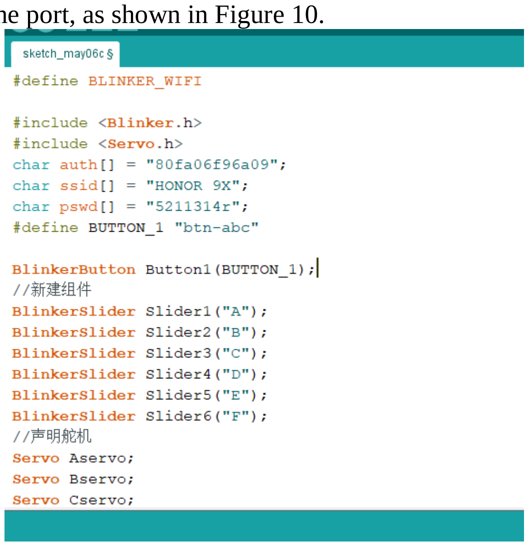


Figure 9 Brushless motor module software design flow chart

4 Adsorption motion test of DHWCR

4.1 Control board debugging

After entering the compilation environment, select the corresponding development board and port, compile and fire the program. When the indicator on the control board is off, open the port and observe the data displayed on the port, as shown in Figure 10.




```
#define BLINKER_WIFI

#include <Blinker.h>
#include <Servo.h>
char auth[] = "80fa06f96a09";
char ssid[] = "HONOR 9X";
char pswd[] = "5211314r";
#define BUTTON_1 "btn-abc"

BlinkerButton Button1(BUTTON_1);
//新建组件
BlinkerSlider Slider1("A");
BlinkerSlider Slider2("B");
BlinkerSlider Slider3("C");
BlinkerSlider Slider4("D");
BlinkerSlider Slider5("E");
BlinkerSlider Slider6("F");
//声明舵机
Servo Aservo;
Servo Bservo;
Servo Cservo;
```

Figure 10 Arduino compilation environment

Before power-on, short connect the GPIO 0 and GND ports of the ESP32-CAM module. This will make the ESP32-CAM enter the download and start mode. Otherwise, the Arduino IDE will report an error. Fritzing simulation software is used to select ESP32-CAM module and USB-to-serial port download, and the circuit simulation connection as shown in Figure 11 is established.

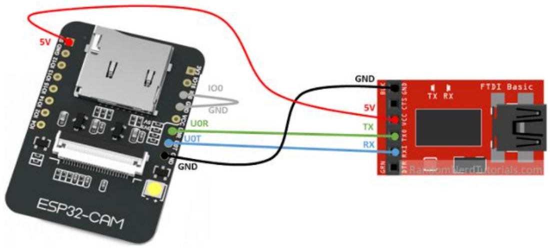


Figure 11 Program download Fritzing simulation wiring diagram

After the test code is burned, disconnect the GPIO 0 from GND, let the ESP32-CAM enter memory startup mode, and then power on the ESP32-CAM again. Open the serial port monitor of the software, select the transmission baud rate, and press the RST button. Open the software serial port. If all is well, the IP is printed on the serial port monitor and can be wirelessly controlled by connecting the Blinker, as shown in Figure 12.

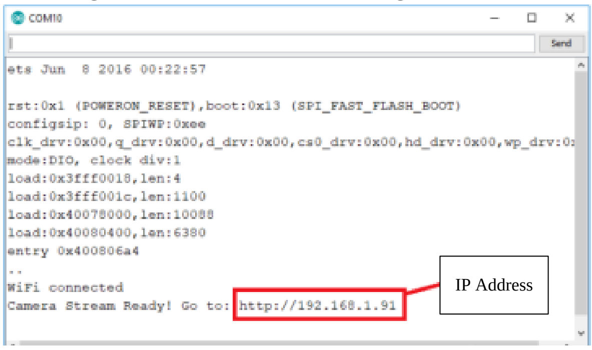


Figure 12 IP address of the serial port

4.2 The complete structure of the DHWCR

The whole machine of the DHWCR mainly includes propeller head, RC receiver, front wheel steering mechanism, propeller steering engine control module, 3D printed body and power supply, as shown in Figure 13. After the overall installation, switch on the power supply of the brushless motor, and test the pulling direction provided by the brushless motor of the front and rear wheels. If the brushless motor of the front and rear wheels provides upward pulling force when they work normally, the wiring is correct; On the contrary, the brushless motor needs to switch the two wires.

In normal operation, the front and rear propeller steering gear rotates 45° respectively, and the front and rear brushless motor generates a tension angle of 45° with the direction of advance. The DHWCR obtains the forward power and the robot walks forward. The fixed propeller head will make the front and rear brushless motors rotate with multiple degrees of freedom, providing different directions of tension angle. The tension generated by the front and rear brushless motors in different directions will generate an angle with the vertical wall, which can ensure that the DHWCR can complete the adsorption movement on the vertical wall.

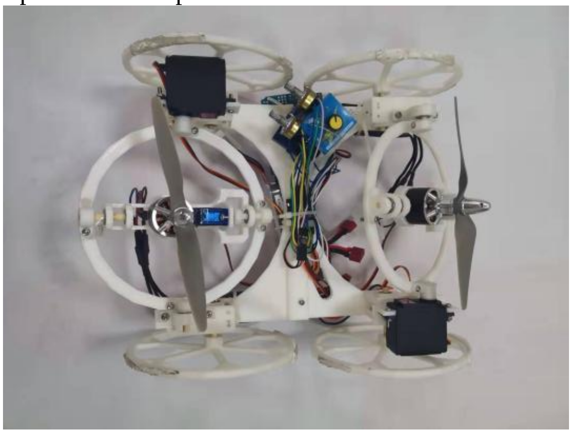


Figure 13 Complete structure of the DHWCR

4.3 Adsorption test of DHWCR

In order to verify the feasibility and stability of the DHWCR in the outer wall, the horizontal ground motion and the wall motion at different angles are tested. The speed of the DHWCR is measured, and the distance of 1m, 2m and 3m is set on the horizontal ground for testing. Each distance is tested three times, and the forward speed is measured by a timer.

Figure 14 The horizontal ground of the DHWCR moves in a straight line

Table 1 Horizontal ground velocity measurement of the DHWCR

Distance /m	No.	Time /s	Velocity m/s	Average velocity m/s
	1	2.69	0.372	
1	2	3.01	0.332	0.351
	3	2.87	0.348	
	1	3.68	0.543	
2	2	4.10	0.487	0.521
	3	3.75	0.533	
	1	4.96	0.605	
3	2	4.58	0.655	0.683
	3	3.80	0.789	

The inclined wall of 30°, 45°, 60° and 75° is designed for test verification. When the DHWCR moved from the ground to the wall at a small angle, under the action of the brushless motor tension, the robot would move directly from the ground to the inclined surface. Figure 15 shows the motion of the DHWCR on the inclined wall of 30°, 45°, 60°and 75°.

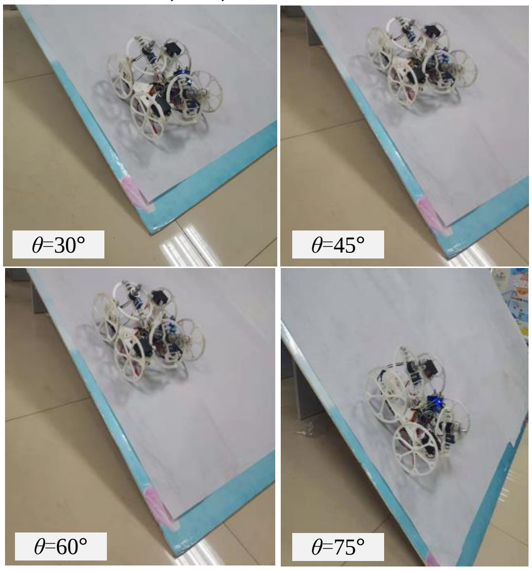


Figure 15 Movement of the inclined wall of 30°, 45°, 60° and 75°

A distance of 1 m and 2 m is set on the vertical wall, and the test is repeated three times for each. The measured velocities are shown in Table 2.

Table 2 Vertical wall velocity measurement of the DHWCR

Distance /m	No.	Time /s	Velocity m/s	Average velocity m/s
	1	14.75	0.068	
1	2	12.36	0.081	0.069
	3	17.09	0.058	
	1	27.53	0.072	
2	2	35.30	0.057	0.064
	3	30.58	0.065	

It can be obtained that the average speed at the horizontal ground distance of 1m, 2m and 3m is 0.351m/s, 0.521m/s and 0.683m/s respectively, and the average speed at the vertical wall crawling distance of 1m and 2m is 0.069m/s and 0.064m/s respectively.

5 Conclusion

In this paper, the hardware and software of the DHWCR are designed and tested for the important problems in the adsorption stability and attitude control. The main conclusions are as follows.

(1) A DHWCR with strong adsorption force and good stability is designed and developed, which is mainly

composed of propeller head, brushless motor module, front wheel steering mechanism module, propeller steering gear control template, wireless handle control module, etc. The left and right control frame with multiple degrees of freedom is designed, which can move on the horizontal ground and vertical wall.

(2) The propeller head and front wheel steering mechanism of the DHWCR can make the robot flexibly switch between the horizontal ground and the vertical wall. In order to ensure that the DHWCR can effectively adsorb, the multi-directional turning drive control is realized, and the movement flexibility is good. By changing the rotation position of the front and rear steering gear and changing the angle of the hub connected with the connecting rod, the DHWCR can achieve smooth steering from left to right and improve the turning efficiency.

(3) Speed test, small slope climbing test and 90 °wall stability adsorption test are carried out on the DHWCR on the horizontal ground and vertical wall. The results show that the DHWCR can switch freely between the horizontal ground and vertical wall, and can stably adsorb on the vertical wall with stable attitude control. The DHWCR moves faster on the horizontal ground than on the vertical wall, which also verifies the feasibility of the robot moving stably on the vertical wall.

The breakthrough of the driving control technology of the new DHWCR has laid a foundation for the nondestructive testing of high-rise buildings and the testing of complex vertical walls.

Conflict of Interest

Te author declare that there is no conflict of interest regarding the publication of this paper.

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