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Development of a Wall-Climbing Robot with Biped-Wheel Hybrid Locomotion Mechanism

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Abstract— **This paper presents a wall-climbing robot for reconnaissance in anti-hijacking application. A novel biped-wheel hybrid locomotion mechanism is proposed, which is composed of a planetary gear train, a vacuum adhesion module and a negative pressure adhesion module. The bipedal, wheeled and hybrid locomotion modes are analyzed respectively. A prototype of the wall-climbing robot with compact size and low power consumption has been developed and a lot of performance tests have been conducted. The experimental results demonstrate that the wall-climbing robot has such characteristics as fast moving speed, excellent surface adaptability and obstacle negotiation capability.**

I. Introduction

The wall-climbing robot has been an interesting topic for more than 40 years. Typical applications include, but not limited to, maintenance of nuclear facilities, inspection of the exterior of large aircraft skin and cleaning of high-rise buildings. Facing an increasingly grim situation of terror in recent years, many researchers turn their attention to developing small wall-climbing robots for surveillance purpose. In anti-terrorism applications, specifically anti-hijacking, wall-climbing robots could replace human operators to perform reconnaissance and surveillance tasks in harsh and difficult-to-access environments. The combination of reconnaissance technology and wall-climbing robot technology will, therefore, provide an alternative tool that will be cheaper, safer and more efficient [1]-[3].

It is well-known that the wall-climbing robots should possess two basic but critical functions: locomotion and adhesion. Research on wall-climbing robot is mainly focused on these two aspects [4]-[6]. Different combinations of locomotion mechanisms and adhesion methods serve different purposes and application scenarios. Based on the locomotion mechanisms, we categorize the existing wall-climbing robots into four types: legged type, wheeled type, tracked type and hybrid type. Each of these mechanisms has advantages and drawbacks. The robots with legged structures typically have two or more limbs and can provide good stability and obstacle negotiation capability, but are generally with large weight, poor maneuverability and mobility [7]-[10]. The robots with wheeled locomotion, commonly two or three wheels, can offer excellent mobility and maneuverability. However, they are difficult to cross over obstacles [11]-[13]. The robots with tracked structures usually present outstanding performance in load capacity and stabilization. But the mobility and maneuverability are not as good as that of wheeled locomotion [14]-[16]. In order to overcome the shortcomings of single locomotion mechanism, robots uniting different locomotion structures emerged. This kind of wall-climbing robot can apply appropriate locomotion mode according to the task demands. Hybrid locomotion mechanism is a new orientation to increase the performance of wall-climbing robots, although this kind of technology is immature [17]-[19].

To design an excellent wall-climbing robot for reconnaissance in anti-hijacking application, rigorous requirements need to be satisfied as follows [20]-[22]: First, the robot needs to have good mobility. Excellent mobility, especially fast moving speed, helps to carry out missions effectively and reliably. Second, fine obstacle negotiation capability is necessary. This allows the robot to cross over various kinds of obstacles in the outer surface of the airplane, such as rivet and intersected planes. Third, the robot should possess superior adaptability to surfaces with different curvatures. This trait is the basis of performing tasks in the exterior of an airplane. Fourth, small size and low noise are essential for the robot. This characteristic will enable the robot to be operational in confined environments. Furthermore, it is in favor of self-concealment with low noise when the robot conducts surveillance tasks.

Based on the research requirements described above, a novel wall-climbing robot with biped-wheel hybrid locomotion mechanism is proposed. The hybrid locomotion mechanism allows the robot to move fast and cross over obstacles easily. Furthermore, this hybrid locomotion mechanism in conjunction with two kinds of adhesion methods improves the adaptability to various surfaces. With these qualities, the robot can meet the basic requirements of performing reconnaissance and surveillance in the exterior surface of an airplane [20].

II. Mechanical System Design

A. Mechanism Design

The basic design idea of the wall-climbing robot is to effectively combine a bipedal mechanism and a wheeled mechanism with a specially designed structure. This design bestows the robot with advantages of the two locomotion

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mechanisms, which can significantly improve the motion performance of the robot.

The prototype of the robot is shown in Fig. 1. This robot includes two modules: negative pressure adhesion module and vacuum adhesion module, which are linked by a special structure of planetary gear train. This structure with the wheeled mechanism installed inside the suction chamber constitutes the biped-wheel hybrid locomotion mechanism. It enables the robot to operate in both bipedal locomotion mode and wheeled locomotion mode. The vacuum sucker and the suction chamber are the two feet of the bipedal locomotion mode, whose design concept is shown in Fig. 2. The wheeled locomotion mode is realized by the 3-wheel locomotion mechanism mounted inside the suction chamber.

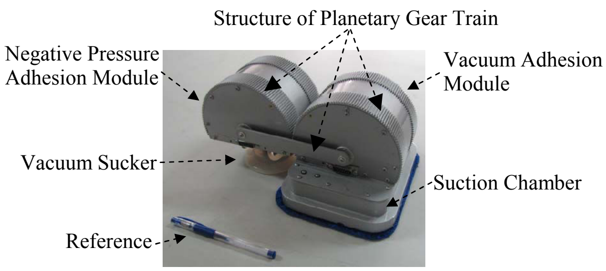

Figure 1. The prototype of the wall-climbing robot

When the robot works in a flat surface that allows the robot to move swiftly, wheeled locomotion mode is adapted. When there are obstacles having to be crossed over in a special task, bipedal locomotion mode or hybrid locomotion mode is used. In addition, the robot can coordinate its hybrid locomotion mechanism, under the hybrid locomotion mode, to realize the transition between two intersecting walls.

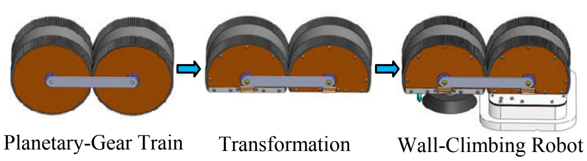

Figure 2. The design idea of planetary-gear train

B. Mechanism Configuration

Fig. 3 is the schematic diagram of mechanism of the robot, which have totally four degrees of freedom. The linear motion unit has one degree of freedom (in up/down direction) and is driven to carry out the movement of contraction and extension of the vacuum sucker. The structure of the planetary gear train, including a sun gear, a planet gear and two arms, possesses one degree of freedom. This special structure combined with the linear motion unit can achieve the bipedal locomotion mode. The wheeled locomotion mode can be accomplished by the 3-wheel locomotion mechanism that is composed of two driving wheels and a supporting wheel, and driven by two motors. It has two degrees of freedom and can perform the motion of moving straight and turning by just adjusting the speed of the two driving wheels. With the two locomotion modes, the robot can achieve complex functions, such as wall transition or obstacle negotiation.

Configuration analysis shows that the special locomotion mechanism provides the robot with the ability to achieve good motion performance by only four degrees of freedom, which effectively reduce the size and weight of the robot without decreasing maneuverability.

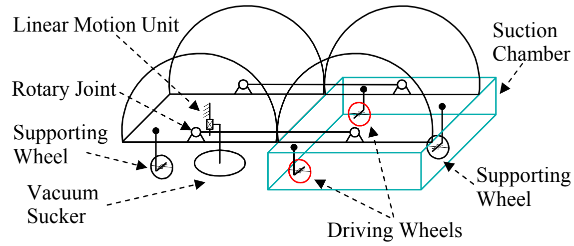

Figure 3. The schematic diagram of mechanism of the robot

C. Adhesion System

The wall-climbing robot applies two kinds of surface adhesion methods to work with the hybrid locomotion mechanism: negative pressure adhesion method adapted by the negative pressure adhesion module and vacuum adhesion method adapted by the vacuum adhesion module.

As shown in Fig. 4-1, the negative pressure adhesion system consists of a centrifugal pump and a suction chamber with a seal perimeter that contacts with the surface to maintain a suitable pressure in the suction chamber. The seal perimeter can keep good sealing effect with its elastic body. Besides, it is coated with a layer of Teflon material to decrease movement resistance of the robot. The design of installing the wheeled locomotion mechanism inside the suction chamber can maximize the advantages of moving fast and turning easily.

As shown in Fig. 4-2, vacuum pump and vacuum sucker are the two major components of the vacuum adhesion system. Installed at the end of the linear motion unit, the vacuum sucker can adjust its position based on the need. Although the vacuum adhesion method has limitation that it operates well only on smooth surface, it can supply strong adhesion force with low noise and power consumption. So, this adhesion method is a suitable choice when the robot performs reconnaissance and surveillance on the airplanes' exteriors where the surface smoothness meets the requirement.

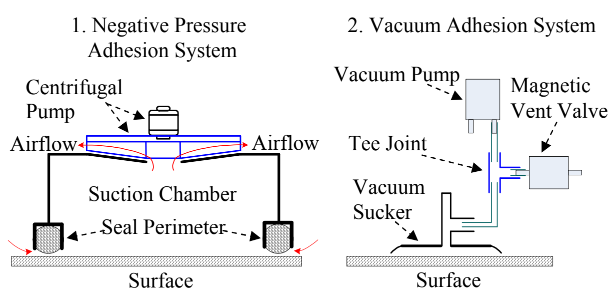

Figure 4. The diagram of the negative pressure adhesion system and the vacuum adhesion system

III. Motion Analysis and Motion Planning

Because of the novelty and specificity of the hybrid locomotion mechanism, accurate motion analysis and planning become essential. This analysis lays foundation to motion control and contributes to maximize motion performance of the wall-climbing robot. Below, the three locomotion modes are analyzed respectively.

A. Motion Analysis

a) Bipedal Locomotion Mode

The bipedal locomotion mode consists of two typical statuses: negative pressure adhesion module supporting (NMS) phase and vacuum adhesion module supporting (VMS) phase. This locomotion mode is analyzed using Denavit-Hartenberg Notation method [23]. Assignments of coordinate systems depend on which module supports the robot. In this paper, the coordinate systems are assigned when the negative pressure adhesion module adheres to the surface, as shown in Fig. 5. The reference frame, frame {0}, is defined in the way the origin of which is in the middle of the two contact points between ground and the two driving wheels. The origin of frame {4}, the final frame, is situated at the center of the vacuum sucker. The link parameters are shown in Table I.

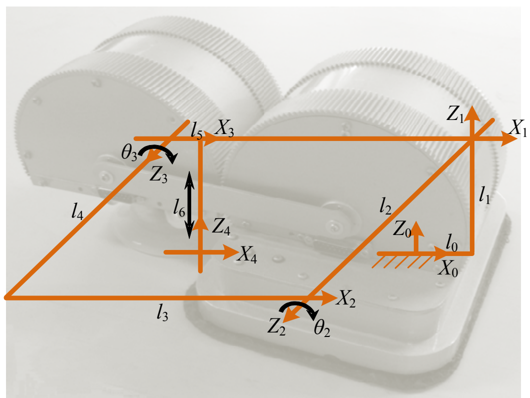

Figure 5. The diagram of the coordinate systems (NMS phase)

TABLE I. LINK PARAMENTERS AND JOINT VARIABLES

i	a_{i-1} [mm]	α_{i-1} [mm]	d_i [mm]	θ_i [°]	Range of Variables	Initial Value
1	l_0	0	l_1	0	Fixed	
2	0	π/2	l_2	θ_2	(-π,0)	0
3	$-l_3$	0	$-l_4$	θ_3	(-π,0)	0
4	l_5	-π/2	$-l_6$	0	($-l_1$-d, $-l_1$+d)	$-l_1$+d

From the view of planetary gear train, the module sticking to the surface performs as sun gear, the other module as planetary gear. The sun gear and the planetary gear are designed with same diameter, so there is equation $\theta_2=\theta_3$ based on the transmission principle of planetary gear train. The basic gait of the bipedal mode is shown in Fig. 6-1, and shaded areas indicate the state of adhesion. The position and orientation of the vacuum sucker can be expressed as (1).

$$ {}^0_4\boldsymbol{T} = {}^0_1\boldsymbol{T}\,{}^1_2\boldsymbol{T}\,{}^2_3\boldsymbol{T}\,{}^3_4\boldsymbol{T} = \begin{bmatrix} c_{23} & 0 & -s_{23} & l_5\cdot c_{23}+l_6\cdot s_{23}-l_3c\theta_2+l_0 \\ 0 & 1 & 0 & l_4-l_2 \\ s_{23} & 0 & c_{23} & l_5\cdot s_{23}-l_6\cdot c_{23}-l_3s\theta_2+l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where, $c\theta$=cosθ, $s\theta$=sinθ, s_{23}=sin($\theta_2+\theta_3$), c_{23}=cos($\theta_2+\theta_3$). l_i represents the length of each link.

b) Wheeled Locomotion Mode

In the status of NMS phase, the robot can also work with the wheeled locomotion mode. By adjusting the speed of the driving wheels respectively, the robot can realize the motion of moving straight and turning easily, as shown in Fig. 6-2. The motion direction of the robot can be expressed by orientation angle θ. As shown in Fig. 7, θ is the angle between axis $\boldsymbol{X}_0$ of reference frame {0} and $\boldsymbol{X}_s$. The global reference frame {$\boldsymbol{X}_s$, $\boldsymbol{Y}_s$, $\boldsymbol{Z}_s$} is fixed to the surface.

The velocity of the robot can be expressed by a 6×1 Cartesian velocity vector that is combination of 3×1 linear velocity vector and 3×1 rotational velocity vector:

$$\boldsymbol{v} = \begin{bmatrix} \boldsymbol{\upsilon} \\ \boldsymbol{\omega} \end{bmatrix}. \quad (2)$$

The velocity of the robot in reference frame {0} can be calculated:

$${}^0\boldsymbol{\upsilon} = \begin{pmatrix} \frac{r\dot{\varphi}_1}{2}+\frac{r\dot{\varphi}_2}{2} \\ 0 \\ 0 \end{pmatrix} \qquad {}^0\boldsymbol{\omega} = \begin{pmatrix} 0 \\ 0 \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \frac{-r\dot{\varphi}_1}{2L}+\frac{r\dot{\varphi}_2}{2L} \end{pmatrix}. \quad (3)$$

$\dot{\varphi}_1$ and $\dot{\varphi}_2$ represent the rotating speed of the two driving wheels, respectively. r represents wheel diameter.

Transforming the frame of velocity is accomplished by means of the following relationship:

$$\begin{aligned} {}^s\boldsymbol{\upsilon} &= {}^s_0\boldsymbol{R}\cdot{}^0\boldsymbol{\upsilon} = \frac{r}{2}\begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ 0 & 0 \end{bmatrix}\begin{pmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{pmatrix} \\ {}^s\boldsymbol{\omega} &= {}^s_0\boldsymbol{R}\cdot{}^0\boldsymbol{\omega} = \frac{r}{2L}\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 1 \end{bmatrix}\begin{pmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{pmatrix} \end{aligned}. \quad (4)$$

In the field of robotics, Jacobians is used to relate joint velocities to Cartesian velocities. The Jacobian written in frame {s} is

$${}^{\upsilon}\boldsymbol{J}(\theta) = \frac{r}{2}\begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ 0 & 0 \end{bmatrix}, \quad {}^{\omega}\boldsymbol{J}(\theta) = \frac{r}{2L}\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 1 \end{bmatrix}. \quad (5)$$

So, the kinematic equation of wheeled locomotion mode can be written as

$$\begin{gathered} \boldsymbol{v} = \boldsymbol{J}\cdot\dot{\boldsymbol{\varphi}} \\ \begin{pmatrix} {}^s\boldsymbol{\upsilon} \\ {}^s\boldsymbol{\omega} \end{pmatrix} = \begin{pmatrix} {}^{\upsilon}\boldsymbol{J}(\theta) \\ {}^{\omega}\boldsymbol{J}(\theta) \end{pmatrix}\begin{pmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{pmatrix} \end{gathered}. \quad (6)$$

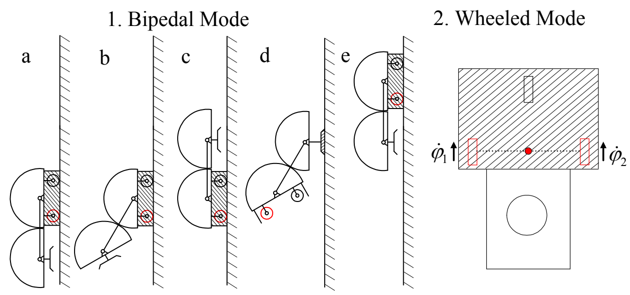

Figure 6. Gait analysis of the two locomotion modes

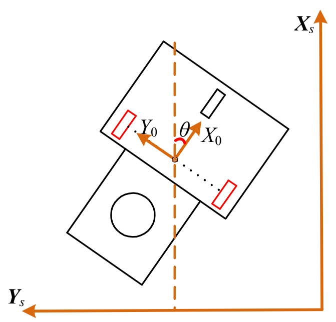

Figure 7. The diagram of wheeled locomotion mode (NMS phase)

c) Hybrid Locomotion Mode

Above sections introduced the theoretical analysis of the two locomotion modes. The wheeled locomotion mode is mainly used for fast movement and steering adjustment. The bipedal locomotion mode plays an important role for obstacle traversing and avoidance. The two movement patterns can be performed separately, and also can be carried out simultaneously to realize the hybrid locomotion mode. As shown in Fig. 8, the concave transition between two intersecting surfaces is analyzed under the hybrid locomotion mode:

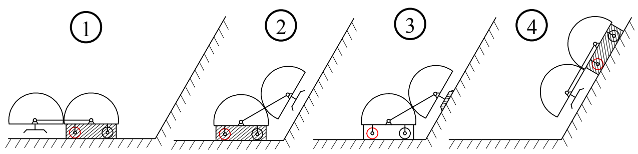

Figure 8. Gait analysis of concave transition

- Approaching the transitional surface. Under the wheeled locomotion mode, the robot moves quickly close to the transitional wall.
- Coarse adjustment. The robot moves to an appropriate location near the wall, while the vacuum adhesion module is driven to the position where the sucker is roughly parallel with the transitional wall.
- Fine adjustment. The distance from the transitional wall, the length of sucker, and the angle of the sucker are all adjusted slightly to let the sucker contact with the wall closely. Then, change the adhesion method to vacuum adhesion.
- Finishing the transition. Drive the negative pressure adhesion module to make it in contact with the wall firmly, and then change the adhesion method again to perform wheeled locomotion mode.

B. Motion Planning

As analyzed above, the robot possesses two basic locomotion modes: wheeled locomotion mode and bipedal locomotion mode. The motion planning of single locomotion mode is relatively simple. This section focuses on the real-time implementation of concave transition between two intersecting walls, which reflects the hybrid locomotion mode.

Based on the analysis of locomotion mode, it is more favorable to carry out the task of wall transition during NMS phase, and the robot can complete it through four steps, as shown in Fig 8. The planning of step 1 and 4 is relatively convenient, so the next analysis is focused on the implementation of step 2 and 3. The relationship of associated parameters is shown in Fig. 9 during step of fine adjustment.

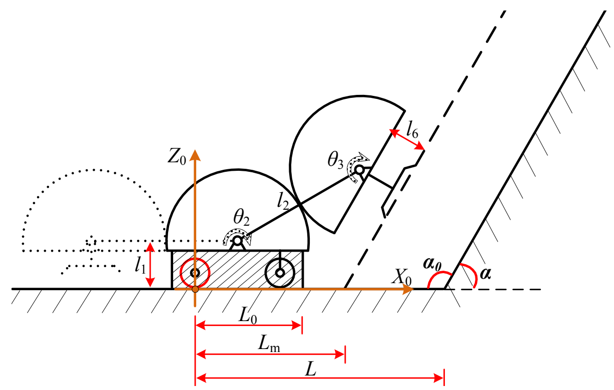

Figure 9. Parameters analysis of wall transition

Based on the corresponding relationship of geometry and turning angle, we have

$$\theta_2 = -\frac{(2\pi - \alpha)}{2} . \tag{7}$$

It is clear that the coordinates of the sucker (p_x, p_z) have the following relationship:

$$\begin{aligned}\tan(2\theta_2 + 2\pi) &= \frac{p_z}{p_x - L_0} \\ &= \frac{l_5 \cdot s_{23} - l_6 \cdot c_{23} - l_3 s\theta_2 + l_1}{l_5 \cdot c_{23} + l_6 \cdot s_{23} - l_3 c\theta_2 + l_0 - L_0}\end{aligned} , \tag{8}$$

where

$$l_6 \in (l_1 - d, l_1 + d) . \tag{9}$$

The value of l_6 must meet the condition that

$$L_m \geq L_0 . \tag{10}$$

Otherwise, the robot will collide with the wall. Although the position of the robot is not fixed, the l_6 should be as small as possible when satisfying the constraints, which make the moment output as small as possible.

When the angle between two intersecting walls is known, the position and joint parameters can be calculated. The relationship between the parameters is shown in Fig. 10.

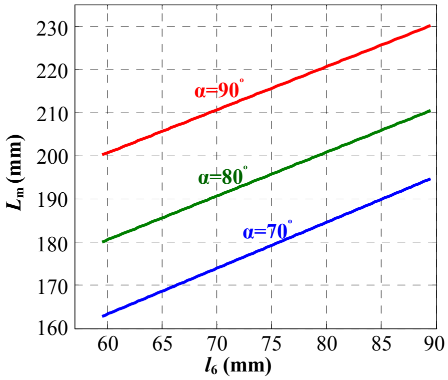

Figure 10. The relationship between the associated parameters

IV. Controller Design

The controller design of the wall-climbing robot should meet the basic demands for reconnaissance. So, the limitations of size, power consumption and heat dissipation of the components have to be considered.

The TMS320F28335 DSP from TI Inc. is selected as the processing unit. This chip can satisfy the requirements from functionality point of view. Also, it has low power consumption and high reliability. Fig. 11 shows the block diagram of the controller based on TI TMS320F28335 DSP chip. Every joint is driven by FAULHABER DC micro-motor with integrated encoder. The chip can process information from pressure sensors, Hall sensors, and encoders. This robot has both wireless and wired control mode. It carries a battery to supply energy in the wireless control mode. In the wired control mode, power and control commands come from a remote base station through RS-232 serial communication.

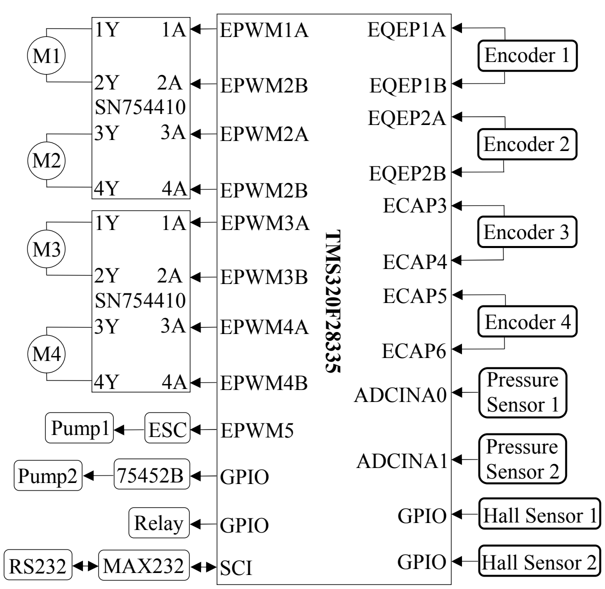

Figure 11. The functional block diagram of the controller

V. Experimental Results

The wall-climbing robot proposed in this paper has been successfully developed. In order to validate the effectiveness of the robot, laboratory and field experiments have been carried out. The contents of the experiments are conducted to test and investigate the surface adaptability, mobility and obstacle negotiation ability of the robot. The basic specifications are listed in Table II.

TABLE II. Specifications of the Robot

Weight [kg]	Size [mm^3]	Noise [db]	Endurance [min]	Range of Surface Transition [°]
1.9	298×212×140	50[a]	> 45	90-180

a. Noise was measured inside the airplane cabin when the robot moves on the exterior of an airplane.

A. *Testing of Surface Adaptability*

As shown in Fig. 12, the robot can safely adhere to and move on many types of surfaces. The test subjects include wood, aluminum alloy, glass and tile. The robot can stick to these surfaces with arbitrary angles while keeping good motion performance. Fig. 12-1 shows the robot is moving in a vertical wood surface with wheeled locomotion mode. Besides planar surfaces, curved surfaces are also tested. As shown in Fig. 12-2, the smallest curvature radius of the aluminum surface the robot can stick to using the negative pressure adhesion method is 1.5 *m*. In the field experiments, the test subject is an airplane, whose average curvature radius is about 2.5 *m*. The robot can execute its two locomotion modes while stably sticking to the outer surface of the airplane, as shown in Fig. 12-4.

B. *Testing of Moving Speed*

With wheeled locomotion mode, the robot has a fast move speed, comparing with robots equipped with other locomotion mechanisms. The speed tests are executed during the above tests. The results are listed in Table III. When moving in aluminum curved surface, the robot's speed can reach to 3 *m/min*, as shown in Fig. 12-2. Its speed is about 4 *m/min* when moving at the bottom of the desk, as shown in Fig. 12-3. The maximum speed the robot can achieve is 5 *m/min* in horizontal surface.

TABLE III. Moving Speed Tests

Material / Angle	Wood	Aluminum alloy	Glass
Horizontal surface	5 *m/min*	5 *m/min*	4 *m/min*
Vertical surface	4 *m/min*	4 *m/min*	3 *m/min*
Curved surface		3 *m/min*	

C. *Testing of intersecting planes transition*

Tests of obstacle negotiation ability include crossing over obstacles with bipedal locomotion mode and transition between two intersecting planes with hybrid locomotion mode. The experimental results show that when the angle between two intersecting planes varies from 90° to 180°, the robot can realize the transition. Fig. 13 shows the basic step sequence of transition between two intersecting aluminum surfaces with angle of 120°, which is consistent with the analysis in section III.

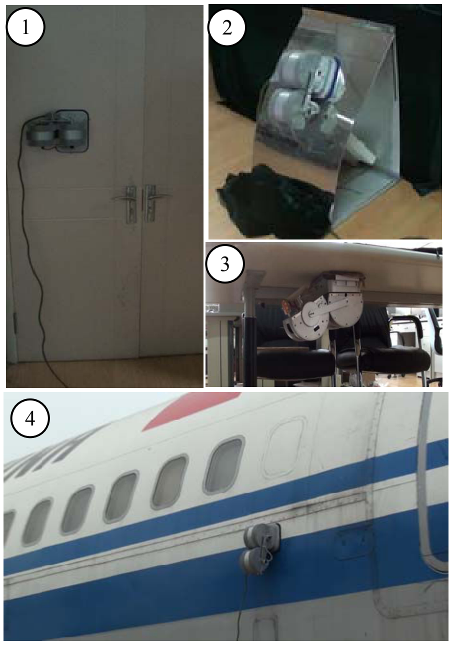

Figure 12. Testing of surface adaptability and moving speed

Figure 13. Testing of concave transition

VI. CONCLUSION

Aimed for anti-hijacking application, a novel wall-climbing robot is introduced. This robot has a biped-wheel hybrid locomotion mechanism based on a specially designed planetary-gear train, which enhances the motion performance of the robot. The experimental results prove that the robot has fast moving speed, excellent obstacle negotiation capability and good surface adaptability, suitable for reconnaissance and surveillance in anti-hijacking tasks. Besides, it fits for many other similar applications.

In future research, the adhesion mechanism will be optimized to improve the load capacity and reduce the noise, which makes the robot more adaptive to the anti-hijacking tasks. Furthermore, the sensor system will be upgraded to enhance the autonomous control ability of the robot.

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