Climbing Reconnaissance Drone Design

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Abstract. At present, multi-rotor UAVs have problems such as weak battery life, short operating time, and difficulty landing on special terrain. This paper has designed a wall-climbing reconnaissance drone. Firstly, the principle analysis and structural design of the support arm and bionic tentacles of the drone are carried out. Then, describes in detail the work process of attaching and off the vertical wall or ceiling. Finally, the dynamic and adhesion process analysis of the structure of the UAV bionic tentacles are performed. The wall-climbing reconnaissance drone overcomes the shortcomings of the traditional drone's short battery life and difficulty landing on special terrain. It has certain development prospects.

1. Introduction

The annual economic losses caused by natural disasters in China amount to hundreds of billions. The effective implementation of fire warning and on-site reconnaissance, and the prompt disposal of the disaster have become increasingly important. The multi-rotor UAV technology [1-3] is maturing and the application fields [4-6] are more and more widespread. However, the battery life is insufficient. Inspired by the climbing of the gecko, this paper designs a bionic gecko mechanical device and integrated it into the drone arm to improve the drone's endurance.

Nowadays, many scientists and technicians at home and abroad have devoted themselves to studying the ability of the bionic gecko's wall climbing. For example, Hanyang University in Korea introduced a new type of connected crawler robot [7]. The robot is based on dry adhesion, characterized by a connecting rod design for climbing obstacles, which solves some important issues in the design of connected climbing walls. A new vacuum pad [8] called the Universal Vacuum Gripper (UVG) was developed by the University of Osaka in Japan. It is based on the Universal Gripper (UG). They evaluated the proposed gripper with grip and adhesion. The Nanjing University of Posts and Telecommunications has proposed a new adsorption method using grippers to clamp rough walls [9]. The simulation and experimental results show that the gripper can fully achieve the adsorption of the rough concrete wall.

2. Drone Structure Design

2.1. Support Arm Structure Design

The four support arms are respectively disposed on the four arms of the four-rotor aircraft. Each support arm is composed of the structures 1, 2, 3, and 4 in Fig. 1. Structure 2 is located at the mid-front of the end of the bracket near the rotor, and is connected by a rotatable structure so that the support arm and bracket can be rotated by 90°. Structures 1 and 3 are fitted with bionic tentacles on their top ends.

When not attached, the structures 1 and 2 are embedded in the bracket and the structure 3 is vertically downward to support the landing of the aircraft. The structure 4 is a rotating motor. When the ceiling or vertical wall is attached, the motor starts. Rotation of the structure 2 causes the support arm to rotate 90° clockwise, so that the structure 1 is vertically upwards, and the top end touches the ceiling to achieve a sticking ceiling. The structure 3 is in the horizontal direction, with the top end touching the vertical wall to achieve adherence, and structure 3 can change the length to accommodate different scenarios. The lower support arm has a telescopic function, and a buffer pad acts as a buffer for the connection between the biomimetic contact pin and the support arm.

(a) (b)

Figure 1. Structure design of support arm: (a) Main view (b) Top view

2.2. Bionic Antenna Structure Design

Bionic antenna using bionic dry adhesive material based on foldable truss structure. Mainly consists of truss, truss springs, truss tendons, orientation adhesives, sticky ribs and latches (see Fig. 2), using multiple directional gecko-like adhesive soles. These adhesives rely on Van der Waals forces for adhesion and can be used repeatedly. The top of the truss is connected to the UAV through a flexible foam connector that can rotate and move during the collision to align the bionic antenna with the drone. The bionic antenna uses a set of brackets to ensure partial alignment before the contact (passive alignment).

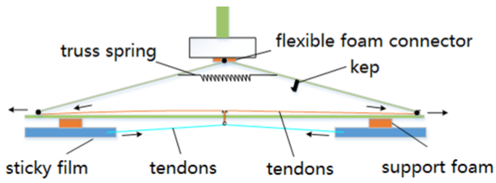

Figure 2. Functional component diagram

When the truss is folded, adopt a low profile attitude to reduce the pitching moment of the UAV attachment wall.

The truss tendons between the legs of the truss will become taut, pulling the adhesive ribs upward displacement, creating an internal shear force that will make the adhesive ribs work. The internal shear force is limited by the length of the truss tendons.

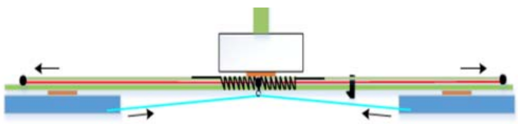

Figure 3. The locked bionic antenna to capture the surface schematic

Energy is absorbed and stored by the truss spring and rebound spring during the collision. When the truss is fully folded, the latch locks the truss, see Fig. 3.

2.3. Overall Structure Design

In order to achieve the absorption of collision energy during the wall-scratching process and the walls without popping, etc. We should follow these principles (see Fig. 4).

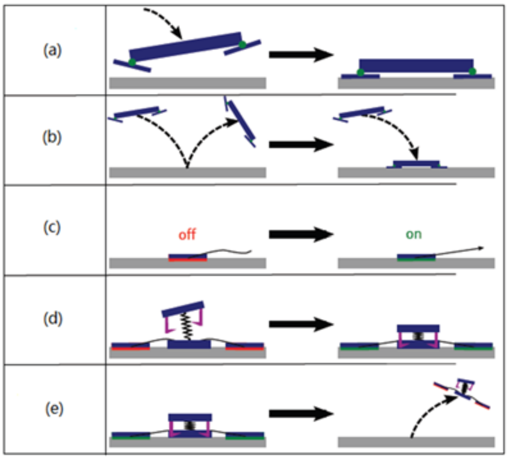

Figure 4. Design principles diagram: (a) Passive alignment principle; (b) Rebound mitigation principle; (c) Adhesion principle of adhesives; (d) System locking principle; (e) Release the adherent principle.

The UAV is equipped with a retractable folding wall bracket, a camera shake-out pan-tilt head and high-definition digital map to complete the reconnaissance work.

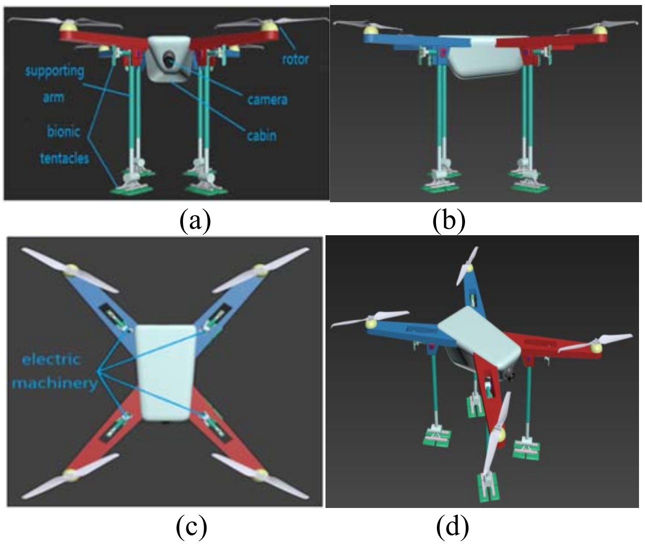

Figure 5. The wall-climbing drone overall structure diagram: (a) Main view; (b) Left view; (c) Top view; (d) Overall view;

The whole drone consists of a frame, a support arm, a wall-climbing structure, a camera, a distance sensor, a rotor, a battery, and an avionics (in a drone body) module (see Fig. 5). the camera is placed on the front of the aircraft and there are cameras on the front and back. The front camera is used for real-time recording of audio data, and the back camera is used to capture wall pictures. The distance sensor is used to detect the distance from the wall and can rotate 120° to expand the monitoring range. The CCD shifting anti-shake technology prevents image blurring due to slight camera shake in the case of large zoom (with a long monitoring distance). Tab.1 shows the parameters of the wall-climbing drone.

Table1.drone parameters table

Content	**Parameter Value**
Maximum load	3400g
Flying speed	4-8m/s
Drone size (mm)	Length / width / height: 2630/50/710
Maximum take-off weight	4000g
Flight protection	(no signal) aircraft hover automatically
Flight resistance	<20m/s
Maximum altitude	5000m
Operating temperature	-20°C- 60°C

3. Drone Work Process

3.1. Attach the Vertical Wall Process

This process is divided into five stages: flight, deceleration, rotation, adherence and attachment (see Fig. 6). After the drone has found a suitable attachment point during the flight, the two arms near the wall rotate the support rod and fold it until it touches the wall. After that, the gecko bionic tentacles attract the wall, the rotor near the wall end slowly rotates and the far wall rotor continues to work, relying on gravity to naturally rotate the drone with the adherent support rod as the axis. Finally, the far wall support rod expands and folds, touching the wall and absorbing it. The drone is now at a 45° angle with the wall, and the far-end rotor stops working to complete the process of attaching a vertical wall.

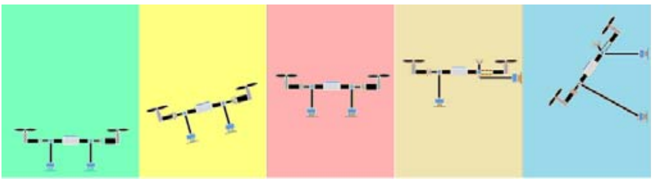

Figure 6. Attach the vertical wall process

3.2. Attach the Ceiling Process

This process is divided into four stages: flight, deceleration, rotation and sticking (see Fig. 7).

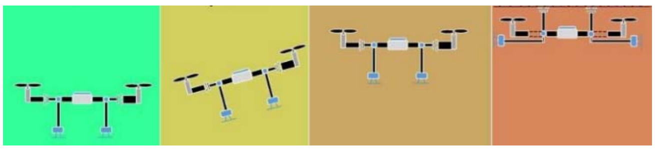

Figure 7. Attach the ceiling process

After the UAV finds a suitable attachment point during the flight, the four arms rotate the support rod during the process of approaching the wall, and then fold until the wall is touched. Finally, the gecko's bionic antennae absorb the walls, and the four rotors stop working to complete the process of attaching the ceiling.

3.3. Off the Vertical Wall Process

This process is divided into four stages of attachment, separation, deceleration, and flight (see Fig. 8).The drone starts the off-board process after the mission is completed. The wing at the far wall begins to work and the tentacles get out of the wall. The support rod rotates back to the initial position and flies to the same height as the arm near the wall. Then the wing near the wall begins to work and the tentacles lift off the wall. The support rod rotates back to the initial position, and then the drone enters a flight state and returns to landing, completing the process of leaving the vertical wall.

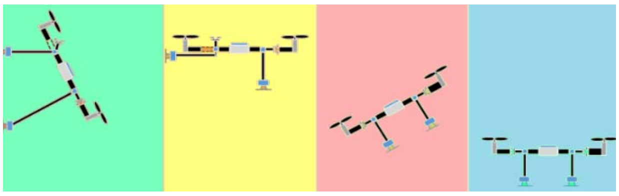

Figure 8. Off the vertical wall process

3.4. Off the Ceiling Process

This process is divided into four stages of attachment, separation, deceleration and flight (see Fig. 9). After the mission is completed, the drone starts the off-board process. The four rotors start working and the speed is checked to determine if the lift force is sufficient to resist gravity. Bionic contact foot off the ceiling and support rod rotation back to initial position. After the drone enters the flight state, it returns to land and complete the process of leaving the ceiling.

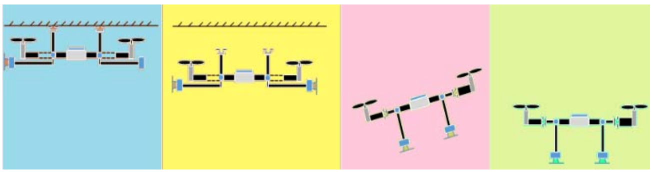

Figure 9. Off the ceiling process

4. Drone Dynamics Analysis

The gravity of the wall-climbing drone can be considered to act evenly on the bottom of the support frame, so equation (1) can be derived.

$$f_{ns} = \frac{F_n}{2S} = \frac{2nf_m - G\sin\beta}{2Lb} \quad (1)$$

Where f_{ns} is the normal support force per unit area of the bionic antenna at the bottom of the support arm support. F_n is the total normal vector support force. L is the length of the bionic antenna and b is the width. S is the total area of the bionic tentacles. G is the gravity of the drone.$f_m$is the adsorption force of a single bionic antenna.n is the number of bionic antennae. The wall angle is $\beta \in [-\pi/2, \pi/2]$.Set the friction coefficient to μ and the lateral friction per unit length is equation (2).

$$f_{fl} = \mu f_{nl} = \mu \frac{F_n}{2L} = \mu \frac{2nf_m - G\sin\beta}{2L} \quad (2)$$

The formula assumes that the bionic antenna is only subject to lateral friction and is distributed evenly over the bionic antenna. The lateral friction and frictional resistance moments between a single bionic antenna and the wall can be derived as shown in equation (3).

$$\begin{cases} F_{fx} = (L/2 - d)f_{fl} - (L/2 + d)f_{fl} = -2d \cdot f_{fl} \\ M_f = (L/2 - d)f_{fl} \cdot (L/2 + d)f_{fl} = f_{fl}(L^2/4 - d^2) \end{cases} \quad (3)$$

Based on the above analysis, the dynamic equation [10] for wall-climbing drone in the general space pose state is transformed into the wall coordinate system as equation (4).

$$\begin{cases} m\ddot{x} = \left(-4f_{fl}d - G\cos\beta\sin\theta\right)\cos\theta - \left(F_i + F_o - G\cos\beta\sin\theta\right)\sin\theta \\ I_c\ddot{\theta} = \left(F_o - F_o\right)\cdot B/2 - 2f_{fl}\left(L^2/4 - d^2\right) \\ m\ddot{y} = \left(-4f_{fl}d - G\cos\beta\sin\theta\right)\sin\theta - \left(F_i + F_o - G\cos\beta\sin\theta\right)\cos\theta \end{cases} \quad (4)$$

According to equation (4), we can make the passive alignment method achieve the desired goal given the kinematic parameters. The bionic antenna must be fully aligned with the wall before tension is applied to the adhesive web. For a collapsible truss, this means that the feet need to apply enough force to overcome the rotational inertia before the sticky sheet touches the wall, otherwise the truss collapses in advance.

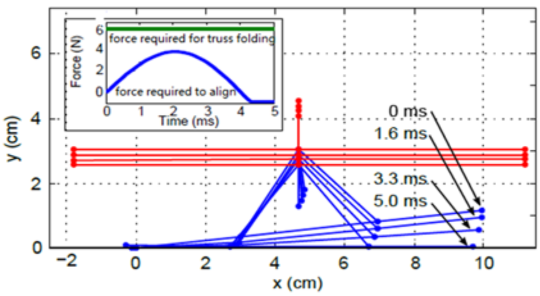

Figure 10. Bionic antenna simulation block diagram in passive alignment

In order to better understand the passive alignment systems, we modeled this system in Motion Genesis software with the help of relevant device size and adherent material properties. The simulation results are shown in Fig. 10, where the incoming speed is 1m/s and the angular deviation is 6.6°. Blue is the reaction force at the top of the truss and green is the force required to fold the truss. This simulation predicts that the maximum reaction force at the top of the truss is approximately 3.8N when the applicator is aligned with the wall in front of the adhesive sheet contacting wall. Below the truss fold force, approximately 5.9N.

5. Analysis Of Adhesive Adhesion Process

The properties of an oriented adhesive can be described in terms of the force space limit curve. However, the limit curve of the bionic antenna is different from the limit curve of a single PSA sheet. For a collapsible truss fixture, we can explore the limit curve of the fixture by using two stick gauge limit curve models. The model is shown in Fig. 11 (a).

The load on the adhesive sheet is the resultant force of the tension at the angle θ generated along the tendons of the adhesive sheet and the compressive force generated by each adhesive sheet supporting the foam sheet. Since the geometry is fixed which the tendons are inextensible, the foam sheet produces a constant force N_{foam}.The force acting on the adhesive sheet is limited to the line segment of the force space with the angle θ and the interception force N_{foam}. And cross the limit curve at the point (S_{max}, N_{max}). See Fig. 11 (b).

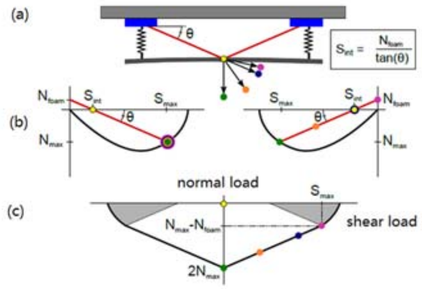

Figure 11. Force analysis and curve of climbing wall structure

If the assumption of a fixed shape is established, the joint limit curve of the bionic antenna is a straight sum of these line segments. That is, a rhombic region in the force space, see Fig.11(c). Along the lower edge of the diamond, the adhesive sheet is at the maximum load N_{max} and the maximum normal load is $2N_{max}$.The area adjacent to the upper edge of the rhombus is the force space and there is no tension in one of the adhesive webs in the force space. This does not mean that the adherent fails, but the geometry is no longer expected to be constant. Therefore , this simple model is no longer accurate. These areas appear gray in Fig. 11(c).

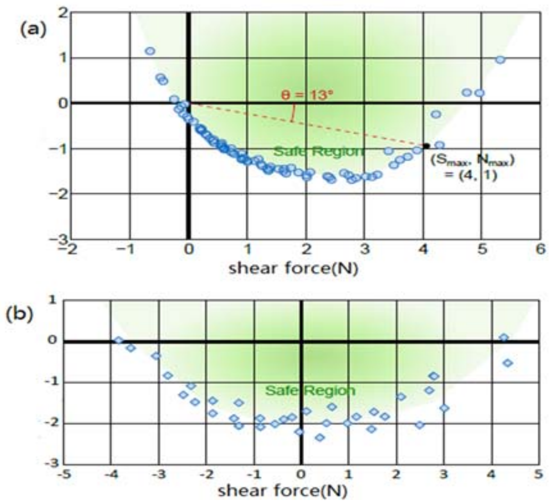

Figure 12. Joint limit curve measurement results

The limit curve of the adhesive sheet is shown in Fig. 12 (a). It can be noticed that the limit curve passes through the origin, which means that the adhesive does not play an adhesive role without shear force. In Fig. 12 (a), a straight line is formed at an angle of 13° to obtain S_{max}=4N and

N_{max}=1N. The maximum normal force for the joint limit

Curve of the adherent can be predicted as $2N_{max}$=2N and the maximum tangential force S_{max}=4N. The joint limit curve measurement results are shown in Fig. 12 (b).

6. Conclusion

1) The combination of a wall-climbing robot and a multi-rotor UAV allows the bottom of the drone support frame to use a bionic dry adhesive material to imitate the structure of the feet of the gecko, so that the aircraft has the ability to attach on the wall. Compared with the sucker type structure, the contact pins of the biomimetic dry adhesive material do not require a high degree of smoothness on the attached wall and the ceiling may be attached if necessary.

2) The four-chassis structure can be used both for landing support and as an attached support rod. In addition, no extra structure has been added. So the overall structure of the UAV is simple and light.

3) After the drone is attached to the wall, the angle of the bracket and the camera can be changed. This increases the angle at which the camera can shoot, and the ability to patrol is greatly improved.

4) The drone can be specifically applied to disaster rescue and military anti-terrorism.

Acknowledgments

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