Analyses on Gliding Pitch Control of Bionic Flying Squirrel Robot

WANG Lingqing, WANG Wei, LI Xuepeng, Zhao Fei, Quan Hualin

Abstract—**Through the bionic principle based on the relevant knowledge of robotics, BSR (Bionic flying squirrel robot) is designed by using the experience of flying squirrel's movement of body structure and mechanism. Besides, control strategy is proposed for pitching movement. In this paper, the mechanism of the robot is introduced first, by which we know the robot is designed by integration and has nine degrees of freedom, which can realize the wall-climbing and gliding movement functions. Then dynamic analysis is used to build a robot kinematics model of gliding pitch movement. Furthermore, the control strategy of gliding pitch movement is discussed. Finally, kinematics simulation, wind tunnel and outfield experiments verify the control strategy achieving the gliding movement. The results show BSR has a good gliding ability based on pitching control strategy.**

Index Terms—**mechanical structure of robot; control strategy; kinematics simulation; wind tunnel and outfield experiments**

I. INTRODUCTION

With the development of bionics, the robot design is more close to real biological configuration and motion. Experienced the long-term natural evolution, flying squirrel can transfer rapidly in the jungle environment with abilities of climbing and gliding [1]. Benefiting from the feature of spatial mobility from two-dimensional environment to three-dimensional space, wall-climbing robot is widely used for operation in nuclear environment, military reconnaissance, maintenance and inspection for hazardous environment, etc.[2, 3]. But wall-climbing robot can't transfer rapidly in three-dimensional space with the single mobile pattern because of low speed. The flying robot can arrive at a target in three-dimensional space quickly but has limited dwell time in the mission due to limited onbroad energy or the loud nosie[4]. So, BSR is proposed to increase the adaptability to different task environments.

Inspired by the body configuration and locomotion mechanism of gecko, some characteristics of gecko's climbing were described according to Zaaf's and Dai's researches [5-7]. (1) The big gecko crawl with diagonal gait, (2) the gecko's driving angle which between body's center line and feet force line of creature usually keep a certain value. These are useful for the structural design of the BSR's wall-climbing model.

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The stability of robots during the gliding process are an essential problem, especially the stability of pitch attitude in the air. Lots of research work both theory and experiment have been done on the posture attitude adjustment for creatures in the air. The main approaches are summarized as follows: (1) Aerodynamic force produced by the air to realize the posture adjustment and control. This kind of creature mainly possess wings, like birds and fruit flies, which use different forms of movements of wings to produce the lift to realize posture change or expand their tails to swing along the different directions to change the flight direction by the corresponding drag [8] . (2) By the swing motion of the other parts of the body to gain posture adjustment such as gecko and lizards, which swing their tails to enhance the stability of aerial statue [9, 10]. Flying squirrel acquires the deformation of membranes to steer the aerodynamic force by adjusting the joints of the four limbs associating with the tail movement. Flying squirrel not only has small physical appearance and configuration, but also has simple gliding control strategy.

Dickson[11] developed ICAROS which adopts the conventional form of glider, with biped wall-climbing mechanism located in the abdominal cavity. When the robot climbs to a certain height, the ICAROS free-falls and entries the gliding mode with the falling velocity of 5.3 $m \cdot s^{-1}$, the gliding ratio of which can approximately reach 2. Essentially, the ICAROS is a kind of gliding robot, because the wall-climbing function is only at the experimental stage and the posture of the robot in the air is adjusted by the tail fin.

Based on the above researches, we put forword the BSR. The robot is designed by integration and has nine degrees of freedom, which can realize the wall-climbing and gliding movement functions. The pitching stability of gliding is the basis of the gliding posture adjustment and combination of climbing-wall and gliding movement. So, in this paper, the main objective is to analyze the stability of the pitching motion of BSR during the gliding process.

The organization of this paper is as follows: In section Ⅱ, we describe our bionic flying squirrel robot and introduce the climbing structure and gliding structure of BSR respectively. In section Ⅲ, we give mathematical model of pitching motion adjustment of BSR, and find that the robot can achieve the adjustment of pitching direction in the gliding process through the tail's movement. Based on the theoretical model, a control strategy of pitching movement is proposed. In section Ⅳ, we do kinematics simulation, wind tunnel and outfield experiments to testify the theoretical model and control strategy. At last, we conclude our studies and describe the future works in section V.

II. MODEL INTRODUCTION AND STRUCTURAL DESIGN OF BSR

A. Mechanical Structure Design of Model

The wall-climbing mode has been researched in our previous work [12] (see Fig. 1). The climbing part is composed of two rigid bodies, four axial legs and a passive waist joint. The trunk is divided into two parts through a pendular waist joint p. As we can see, the climbing part has four prismatic pairs with four axial legs driven by motors.

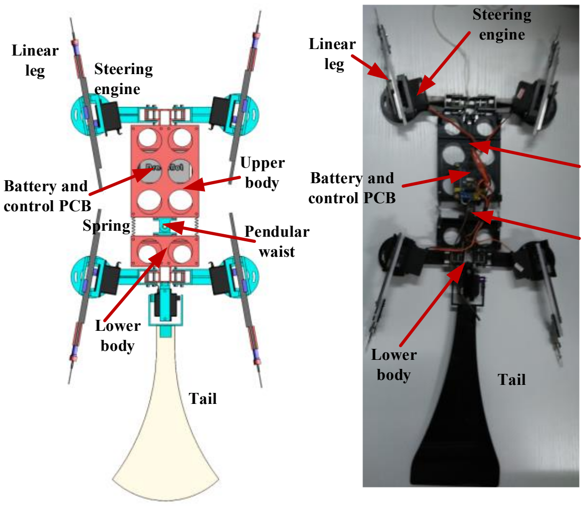

Figure 1. Wall-climbing part of BSR.

The robot is attached to the wall by its linear legs and moves by stretching linear legs.

According to LI's researches about gliding robot [13], the flying squirrel uses patagium attached to the limbs to achieve glide landing. When the flying squirrel is in stable gliding condition, the limbs unfold and patagium is distracted. By changing the shape of wing membranes with limbs, the flying squirrel can adjust the yaw attitude. Besides the flying squirrel adjusts the pitch attitude with the upper or lower motion of the tail. Based on the concept of motion bionics, the mechanical part of gliding is introduced as shown in Fig. 2.

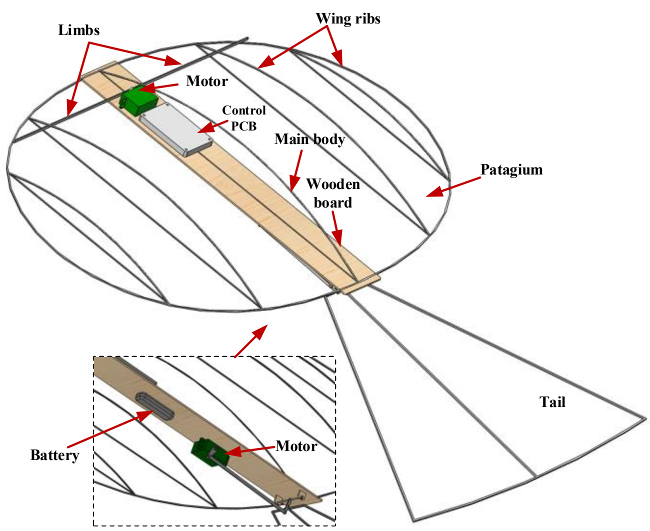

Figure 2. Gliding part of BSR

The gliding part consists of the limbs with rotational joints, main body, tail, wing ribs, patagium and control system with a battery. Here, the patagium covers on the main body by connecting with the ends of the limbs and wooden board. Wing ribs are used to keep certain camber for the patagium. The patagium made of thin silicone membrance is flexible and can change shape with the limbs' movement, which is essential for the posture adjustment in the gliding process of the robot. In addition, the limbs can rotate around the relevant fixed axis driven by motors. The tail can rotate up and down around the relevant fixed axis which is perpendicular to the longitudinal axis of the robot.

B. Bionic Flying Squirrel Robot Prototype

Combined with the design of wall climbing mechanism and gliding mechanism, BSR (Bionic flying squirrel robot) is proposed shown in Fig. 3.

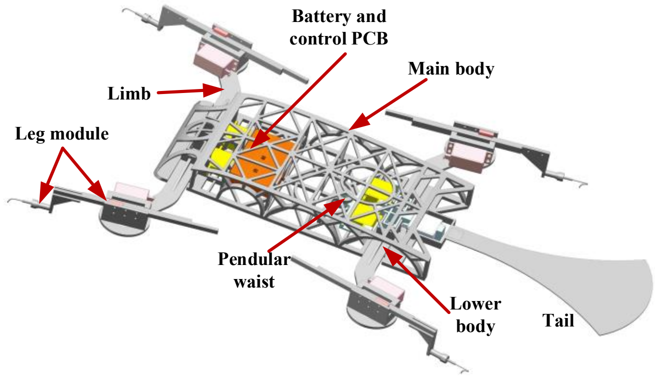

Figure 3. Bionic flying squirrel multi-mode robot

BSR consists of the main body, lower body, pendular waist, tail and limbs with the leg modules, in which the lower body is connected with the main body by the waist rotating joint. BSR has nine degrees of freedom, four prismatic pairs in four axial legs driven by motors and five revolute pairs in four limbs and tail, which make BSR can realize the wall-climbing and the gliding movement respectively. By stretching out and drawing back leg modules and keeping limbs fixed, the robot can achieve the function of wall-climbing, in which the pendular waist plays a significant role in improving the mobility of the wall-climbing robot. The patagium (mentioned in Fig. 2) covering the streamlined main body is attached to the ends of the limbs. BSR acquires suitable velocity by free-falling and enters into the gliding mode by means of adjusting membrane shape and robot posture. In stable gliding process, the movement of the four limbs and tail can control the gliding posture in the air.

III. THEORETICAL MODEL AND CONTROL STRATEGY

In this part, the theoretical model of BSR is given by the kinematics and kinetic analysis of the gliding process. Because of the non-interference between the climbing process and the gliding process, analyses of the climbing-wall and gliding movement can be carried out separately. In the process of climbing wall, the feasibility of using diagonal gait has proved by Zhu [12]. Because the stability of pitching direction is the basis of attitude adjustment, so we focus on the analysis of the pitching stabilization problem in the stable gliding phase.

A. Mathematical Model of Pitching Motion Adjustment

The dynamics of gliding mechanism is the basis of the motion control for bionic robot, which refers to the multi-rigid-body dynamics, aerodynamics and so on. This paper lays stress on gliding pitch control of bionic flying squirrel robot. To simplify the dynamic analysis of gliding mechanism, we make the assumption that the main body's aerodynamic center is located at the quarter-chord point and the tail's aerodynamic center is located at its gravity center. Hence, the whole aerodynamic forces act on the aerodynamic center in the following theoretical analysis.

The forces applied to the flying squirrel consist of aerodynamics and gravity in gliding phase. The resultant aerodynamic force R consists of lift L and drag D, as shown in Fig. 4.

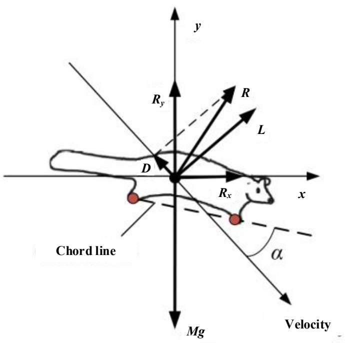

Figure 4. Mechanical model of gliding creatures

In the stable gliding phase, just as mentioned before, the stability of pitching direction plays an important role in attitude adjustment. So, a simplified gliding prototype of BSR is made for the analysis of the pitching stabilization problem in the stable gliding phase (see Fig. 5).

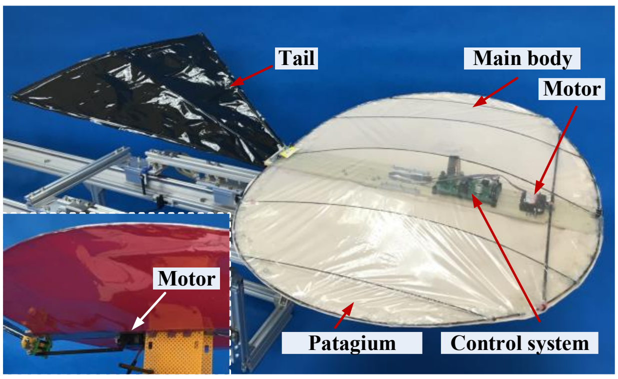

Figure 5. Simplified gliding model of pitching motion adjustment. Tail's movement is drived by motor

The pitch motion is adjusted by changing the aerodynamic forces and multi-rigid-body dynamics of tail together. In order to analyze aerodynamic effects, the whole aerodynamic model can be divided into two components: main body attached membrane and tail. The main body adopts the NACA 6412 airfoil profile to obtain high aerodynamic performance and the tail is designed to adjust the pitching posture by corresponding rotational movement. Similarly, the tail is composed of tail-frame and membrane, which is driven by the motor. Since the aerodynamic performance of the main body and tail are different, we analyze the aerodynamic forces of the main body and the tail separately. The mechanical model is shown in Fig. 6.

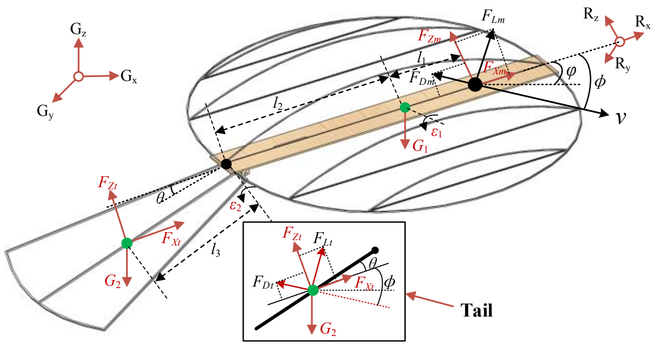

Figure 6. Simplified gliding mechanical model of BSR. Green circles are lumped masses G_1 and G_2, which represent the combined mass of the main body and tail. l_1 is the distance between the main body's aerodynamic center and the G_1. l_2 is the distance between the revolute pairs of tail and G_1, l_3 is the distance between the revolute pairs of tail and G_2. F_L, F_D are aerodynamic lift and aerodynamic drag respectively.

ϕ, φ and ε_1 are the angle of attack, the pitch angle and the pitching angular acceleration of the main body. θ, ε_2 are the pitch angle and angular acceleration of the tail. Gx-Gy-Gz is the global coordinate system, and Rx-Ry-Rz is the local coordinate system of the robot. So the kinetic equation can be got as below:

$$\begin{cases} F_{Ab} = \left[F_{Lm} \quad F_{Dm}\right]^T = \dfrac{\rho S_1 v^2}{2}\left[C_{L1} \quad C_{D1}\right]^T \\ F_{At} = \left[F_{Lt} \quad F_{Dt}\right]^T = \dfrac{\rho S_2 v^2}{2}\left[C_{L2} \quad C_{D2}\right]^T \end{cases} \tag{1}$$

Where, F_{Ab}, F_{At} are the resultant aerodynamic force of main body and tail respectively. ρ is the density of air, v is the velocity of oncoming airflow. S_i is the effective area of main body or tail. C_{L1}, C_{L2} and C_{D1}, C_{D2} are the lift and drag coefficients of main body and tail respectively. They are functions of the angle of attack and can be obtained in Ref. [14-15].

L_b, L_t are obtained by decomposing the aerodynamic forces along the direction of the chord line and perpendicular to chord line.

$$\begin{cases} L_b = \left[F_{Zm} \quad F_{Xm}\right]^T = \begin{bmatrix} \cos\phi & \sin\phi \\ \sin\phi & -\cos\phi \end{bmatrix} F_{Ab} \\ L_t = \left[F_{Zt} \quad F_{Xt}\right]^T = \begin{bmatrix} \cos\phi & \sin\phi \\ \sin\phi & -\cos\phi \end{bmatrix} F_{At} \end{cases} \tag{2}$$

In the local coordinate system Rx-Ry-Rz, The additional torque (M_1) of main body due to the tail adjustment can be obtained by the following formula:

$$M_1 + J_t \varepsilon_2 = 0 \tag{3}$$

Where, J_t and ε_2 are the rotational inertia and angular acceleration of the tail.

The additional torque resulting from the change of the center of gravity due to swing of the tail can be ignored. And suppose the center of gravity of the robot's main body is on the chord line. Based on (2) ~ (3) , the torque of the robot's main body at G_1 as below:

$$M = M_1 + F_{Zm} l_1 - F_{Zt}(l_3 \cos\theta + l_2) + F_{Xt} l_3 \sin\theta \quad (4)$$

According to (4), Theoretical analysis shows that by adjusting the motion of the BSR's tail, the robot can change the pitching torque in the gliding process.

When the tail is stationary, the additional torque (M_1) of main body due to the tail adjustment is 0. If the current pitch motion is in a stable state, the pitching moment generated by the aerodynamic torque should be 0.

$$F_{Zm} l_1 - F_{Zt}(l_3 \cos\theta + l_2) + F_{Xt} l_3 \sin\theta = 0 \quad (5)$$

The tail adjustment angle can be obtained in the steady state of the pitching motion as follow:

$$\theta = \arcsin\left(\frac{F_{Zt} l_2 - F_{Zm} l_1}{l_3 \| L_t \|_2}\right) + \gamma \quad (6)$$

Where,

$$\begin{cases} \gamma = \arctan \dfrac{F_{Zt}}{F_{Xt}} \\ \|L_t\|_2 = \sqrt{F_{Zt}^2 + F_{Xt}^2} \end{cases} \quad (7)$$

In the steady glide phase, due to the vertical velocity change or the effect of the outside wind, the pitch torque of main body will change and the angular acceleration ε_1 (could be measured by sensor on control system) of the pitch direction will be generated. In order to avoid instability, according to the Eq. (3), we can get:

$$|\varepsilon_2| \geq \frac{J_m |\varepsilon_1|}{J_t} \quad (8)$$

Where, J_t and J_m are the rotational inertia of the tail and main body.

The velocity v, pitch angle φ and pitching angular acceleration ε_1 of the main body can be obtained by the sensor of the control system. So according to the velocity v and pitch angle φ, attack angle ϕ could be calculated. As a result, according to the Eq. (6) and (8), by applying the corresponding angle and angular acceleration (θ, ε_2) to the tail, the pitching stability could be realized.

B. Control Strategy for Pitch Posture Adjustment

According to the above theoretical analysis, we can find that tail's swing is in charge of the pitch posture adjustment. Similar to the aileron of aircrafts, the robot generates the uptrend aerodynamic moment when the tail swings up, as shown in Fig. 7. In contrast, the robot generates the downtrend aerodynamic moment when the tail swings down. In addition, the angular acceleration of the tail also generates the corresponding aerodynamic moment which can be obtained by multi-rigid-body dynamics analysis (see Eq. (3)).

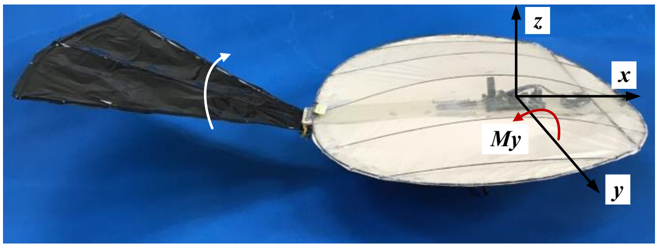

Figure 7. Tail swings for pitch posture adjustment

A simple gliding pitch control strategy is proposed. When the pitch angle is smaller than the target pitch angle, tail swings up with (θ, ε_2) got by Eq. (6) and (8). When the pitch angle is bigger than the target pitch angle, tail swings down.

The structure of pitch angle controller is given as shown in Fig. 8. Target pitch angle is given, and output pitch angle can be measured with gyroscope on the control system. The transfer function is got by Eq. (6) and (8). So, the (θ, ε_2) of tail can be known with PID controller and transfer function.

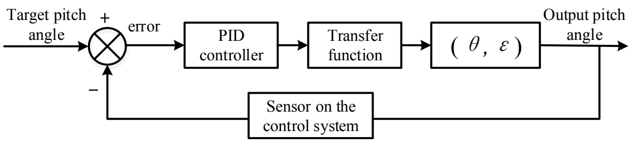

Figure 8. Gliding pitch control strategy of BSR

IV. KIINEMATICS SIMULATION AND EXPERIMENTS OF BSR

A. Kinematics Simulation of the Gliding Model

Based on above theoretical analysis, we find that the angular acceleration of tail can induce additional pitching torque on the main body. In order to verify the effect of tail motion on pitch adjustment, the simplified gliding model (see Fig. 5) was simulated in ADAMS. The corresponding simulation parameters of gliding model are listed in Table I.

TABLE I. SIMULATION PARAMETERS

Parameters	*value*	*Parameters*	*value*
Quality of model	240g	Length*width	830mm*620mm
Target pitch angle	0°	Initial angle velocity	25°/s
Initial X velocity	6 m/s	Initial Y velocity	0 m/s

When the tail stops adjusting, the robot rotates about 25°/s, and the pitch angle keeps increasing with time (Fig. 9 (0 rad/s)). Sinusoidal motion with different angular frequency is applied to the tail to analyze the effect of the tail rotation on the main body. It can be found that the angular frequency of the tail rotation has obvious influence on the pitch stabilization as shown in Fig. 9 (5π-15π rad/s). It is easy to find that the pitch angle can be stable in a small range at a certain angular frequency (about 10π rad/s).

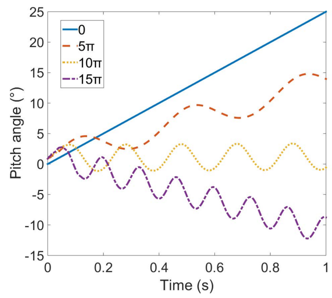

Figure 9. Main body's pitch angle with different angular frequency of tail rotation

In this simulation, when the tail motor angular frequency is 10π rad/s, the absolute value of pitching angle is not more than 3.5° which is close to the target angle 0°.

Combined with Eq. (3) and above simulation, it can be found that the additional torque generated by the tail's angular acceleration (ε_2) can adjust the pitch of the main body well. Besides, the simulation result of tail's angular frequency is helpful to the setting of sampling period in the actual gliding experiment.

B. *Wind Tunnel Experiment*

In this paper, the wind tunnel experiment is performed at D1 open–circuit low-speed wind tunnel in Beihang University, China. Here, the D1 wind tunnel is with an oval working section of 1.02 m × 0.76 m inlet and 1.07 m × 0.82 m outlet and turbulent intensity less than 0.3%. It adopts the SCR controlled stepless speed regulation form and the maximum wind speed can reach 50 m·s^{-1}. Its main specification parameters are shown in Table II.

TABLE II. PARAMETERS OF D1 WIND TUNNEL

Parameters	*value*	*Parameters*	*value*
Inlet geometry (m^2)	1.02*0.76	Outlet geometry (m^2)	1.07*0.82
Length of working section (m)	1.45	Turbulent intensity (%)	<0.3
Regulator form of wind speed	SCR controlled stepless speed regulation	Maximum wind speed (m·s^{-1})	50

An experimental platform is designed to research the aerodynamic effect of the angle of the tail in gliding process, as shown in Fig. 10. The gliding robot is installed on the strain balance by the connector. The angle of attack of the robot can be changed by the adjusting device. Meanwhile, the tail's movement are controlled by tail's motor. Here, the wind tunnel system, the robot and adjusting device for angle of attack are all controlled by PC. The aerodynamic torque is collected in real time by the strain balance and recorded by PC.

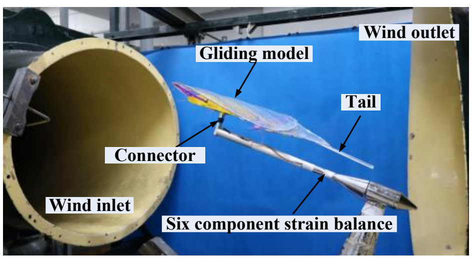

Figure 10. Wind tunnel experimental paltform

The whole experiments are conducted in static condition, where the aerodynamic forces are measured after the adjustments of main body's attack angle and pitch angle of tail. Therefore, only the pitch angle of tail and angle of attack are considered in the motion parameters. In the experiment, to explore aerodynamic effect of pitch angle of tail, we design the following wind tunnel experiment: wind speed is 6 m·s^{-1}. The pitch angle (θ) of the tail is used to represent the motion state of tail. The range of pitch angle of tail (θ) and angle of attack (φ) are [−10°, 20°] and [−16°, 20°], respectively.

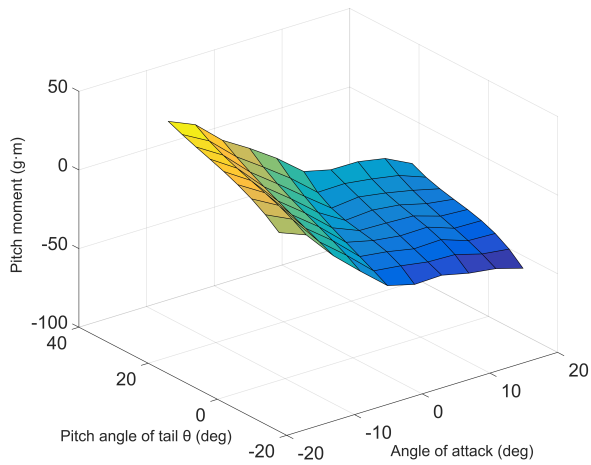

Figure 11. The pitch moments variation space of (ϕ, θ)

The results of tunnel experiment is shown as Fig. 11. According to Fig. 11, the pitching moment exhibits a linear trend with θ and its variation changes obviously. Besides, the pitching moment decreases linearly with angle of attack ϕ, accompanied with the large variation of pitching moment. These findings reinforce the rationality of flying squirrel's gliding strategy that the pitch angle (θ) of tail caused by tail's movement leads to the change of aerodynamic moment.

C. *Outfield Experiment*

To testify the feasibility of control strategy of pitch posture adjustment we built the physical prototype as shown in Fig. 5 and set up the gliding experience platform as shown in Fig. 12. The platform consists of the launcher and ejection device. The photoelectric switch is used to measure the launching speed of the robot. The ejection device uses a rubber band like slingshot and acts on the back end of the robot by a boosting launcher when carrying out the gliding experiment. Thus, the robot prototype can take off in a certain velocity and direction.

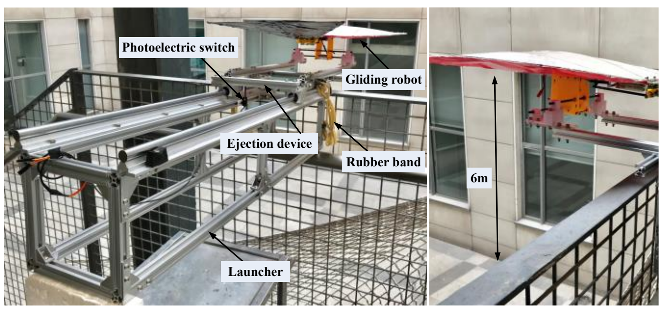

Figure 12. The gliding experience platform

The initial gliding velocity of prototype is 6m/s. And the target angle is 0°. Gliding pitch control strategy in section III was used in the experiment with sampling period of 200ms. Based on the platform and control strategy, the pitch posture adjustment experiences are carried out, as shown in Fig. 13. The pitch posture data is measured by the attitude angle sensor built into the control system, as shown in Fig. 14.

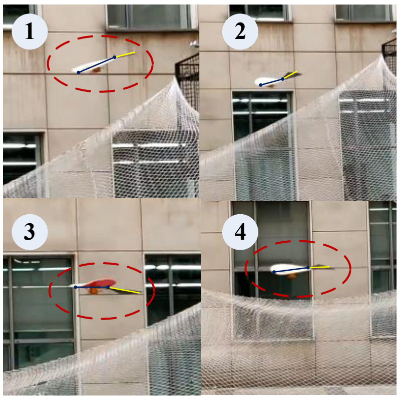

Figure 13. The tail swings up and down for pitch posture adjustment

As shown in Fig. 13, it can be clearly seen that the pitch posture of prototype is adjusted by tail and the pitch motion of the robot gradually becomes stable.

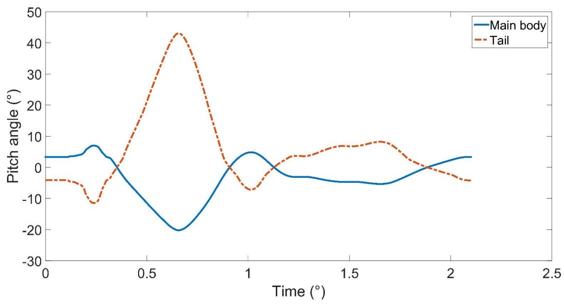

Figure 14. The pitch angle variation of main body with tail's motion

When the pitch angle is reduced by the external factor such as wind or initial state of launcher, the tail can adjust the pitch angle to keep it within the range (-5°, 5°), as shown in Fig. 14. The outfield experiment proves the feasibility of BSR for pitch posture adjustment with the control strategy. In addition, the pitch angle of main body change smoothly and can be controlled within a small range.

V. Conclusion

In this paper we propose the BSR model. To gain a deeper understanding of BSR from a robotic system perspective, the kinematics and aerodynamic modelling, kinematics simulation, wind tunnel and outfield experiments are finished. The following conclusions can be obtained:

(a) Through the mechanical structure design, BSR can realize the wall-climbing and gliding movement functions.

(b) The aerodynamic and additional torque generated by tail's pitch angle and angular acceleration can adjust the pitching stability of the robot during the stable glide stage with a control strategy.

In general, it is feasible for BSR to glide with the control strategy. The combination and switching mode of climbing and gliding motion is also a research direction.

Acknowledgment

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